ATTAINABLE COMPRESSIVE STRENGTH OF PERVIOUS CONCRETE PAVING SYSTEMS

by

ANN MARIE MULLIGAN
B.A. University of Central Florida, 1995
B.S. University of Central Florida, 2003

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil Engineering
in the College of Engineering
at the University of Central Florida
Orlando, Florida

Summer Term
2005

ABSTRACT

The pervious concrete system and its corresponding strength are as important as its permeability characteristics. The strength of the system not only relies on the compressive strength of the pervious concrete but also on the strength of the soil beneath it for support. Previous studies indicate that pervious concrete has lower compressive strength capabilities than conventional concrete and will only support light traffic loadings. This thesis investigated prior studies on the compressive strength on pervious concrete as it relates to water-cement ratio, aggregate-cement ratio, aggregate size, and compaction and compare those results with results obtained in laboratory experiments conducted on samples of pervious concrete cylinders created for this purpose. The loadings and types of vehicles these systems can withstand will also be examined as well as the design of appropriate thickness levels for the pavement.

Since voids are supposed to reduce the strength of concrete 1% for every 5% voids(Klieger, 2003), the goal is to find a balance between water, aggregate, and cement in order to increase strength and permeability, two characteristics which tend to counteract one another. In this study, also determined are appropriate traffic loads and volumes so that the pervious concrete is able to maintain its structural integrity. The end result of this research will be a recommendation as to the water-cement ratio, the aggregate-cement ratio, aggregate size, and compaction necessary to maximize

compressive strength without having detrimental effects on the permeability of the pervious concrete system.

This research confirms that pervious concrete does in fact provide a lower compressive strength than that of conventional concrete; compressive strengths in acceptable mixtures only reached 1700 psi. Extremely high permeability rates were achieved in most all mixtures regardless of the compressive strength. Analysis of traffic loadings reinforce the fact that pervious concrete cannot be subjected to large numbers of heavy vehicle loadings over time although pervious concrete would be able to sustain low volumes of heavy loads if designed properly. Calculations of pavement thickness levels indicate these levels are dependent on the compressive strength of the concrete, the quality of the subgrade beneath the pavement, as well as vehicle volumes and loadings.

ACKNOWLEDGMENTS

A warm thanks is extended to my family and friends for their unwavering support. A deepest appreciation is sent to my advisor, Dr. Manoj Chopra, whose help, support, and guidance allowed this thesis to come to fruition. I would also like to recognize my committee members, Dr. Martin Wanielista and Dr. Shiou-San Kuo, for their help, advice, and interest in improving the quality of this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS/ABBREVIATIONS

A/C Ratio	Aggregate-Cement Ratio
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ASTM	American Society for Testing and Materials
C_d	Drainage Coefficient
E_c	Elastic Modulus of Concrete in psi
f'_c	Compressive Strength of Pervious Concrete in psi
GY	Total Growth Factor
in	inches
J	Load Transfer Coefficient
k	Modulus of Subgrade Reaction in pci
lbs	Pounds
min	Minute
p_o	Initial Serviceability Index
p_t	Terminal Serviceability Index
?PSI	Change in Serviceability Index
PCA	Portland Cement Association
psi	Pounds per square inch
R	Reliability in percent
S_o	Standard Deviation
S_c	Modulus of Rupture of Pervious Concrete in psi

sk per cu yd	Sack per Cubic Yard
T	Percentage of Trucks in ADT
T_f	Truck Factor
vs	Versus
W/C Ratio	Water-Cement Ratio
Z	Standard Normal Deviate

1.0 INTRODUCTION

1.1 Definition

Pervious concrete is a composite material consisting of coarse aggregate, Portland cement, and water. It is different from conventional concrete in that it contains no fines in the initial mixture, recognizing however, that fines are introduced during the compaction process. The aggregate usually consists of a single size and is bonded together at its points of contact by a paste formed by the cement and water. The result is a concrete with a high percentage of interconnected voids that, when functioning correctly, permit the rapid percolation of water through the concrete. Unlike conventional concrete, which has a void ratio anywhere from 3-5%, pervious concrete can have void ratios from 15-40% depending on its application. Pervious concrete characteristics differ from conventional concrete in several other ways. Compared to conventional concrete, pervious concrete has a lower compressive strength, higher permeability, and a lower unit weight, approximately 70% of conventional concrete. Figure 1.1.1 provides a photograph of in-situ pervious concrete and Figure 1.1.2 shows pervious concrete compared with conventional concrete.

Figure 1.1.1 Pervious Concrete

Figure 1.1.2 Comparison of Conventional Concrete and Pervious Concrete

1.2 History

Pervious concrete had its earliest beginnings in Europe. In the 19th century pervious concrete was utilized in a variety of applications such as load bearing walls, prefabricated panels, and paving. In the United Kingdom in 1852, two houses were constructed using gravel and concrete. Cost efficiency seems to have been the primary reason for its earliest usage due to the limited amount of cement used.

It wasn't until 1923 when pervious concrete resurfaced as a viable construction material. This time it was limited to the construction of 2-story homes in areas such as Scotland, Liverpool, London, and Manchester. Use of pervious concrete in Europe increased steadily, especially in the post World War II era. Since pervious concrete uses less cement than conventional concrete and cement was scarce at the time, it seemed that pervious concrete was the best material for that period. Once again housing construction was its primary use. Pervious concrete continued to gain popularity and its use spread to areas such as Venezuela, West Africa, Australia, Russia, and the Middle East.

Since the United States did not suffer the same type of material shortages as Europe after World War II, pervious concrete did not have a significant presence in the United States until the 1970's. Its use began not as a cheaper substitute for conventional concrete, although that was an advantage, but for its permeability characteristics (Ghafoori, 1995). The problem encountered in the United States was that of excessive runoff from newly constructed areas. As more land development took place the amount of impervious area increased. This produced an increase in runoff which in turn led to flooding. This had a negative impact on the environment, causing erosion and a degradation in the quality of water. Pervious concrete began in the states of Florida, Utah, and New Mexico but has rapidly spread throughout the United States to such states as California, Illinois, Oklahoma, and Wisconsin.

Although it had sluggish beginnings, the use of pervious concrete as a substitute for conventional concrete has grown into a multi-functional tool in the construction industry.

1.3 Uses

Practical for many applications, pervious concrete is limited by its lack of durability under heavy loads. This lack of resiliency restricts the use of pervious concrete to specific functions. Pervious concrete is limited to use in areas subjected to low traffic volumes and loads. Although once used as load bearing walls in homes (Ghafoori, 1995), pervious concrete is now utilized primarily in parking lots but does have limited applications in areas such as greenhouses, driveways, sidewalks, residential streets, tennis courts (limited to Europe), and swimming pool decks.

1.4 Advantages and Disadvantages

Pervious concrete is advantageous for a number of reasons. Of top concern is its increased permeability compared with conventional concrete. Pervious concrete shrinks less, has a lower unit weight, and higher thermal insulating values than conventional concrete.

Although advantageous in many regards, pervious concrete has limitations that must be considered when planning its use. The bond strength between particles is lower than conventional concrete and therefore provides a lower compressive strength. There is potential for clogging thereby reducing possibly its permeability characteristics. Finally, since the use of pervious concrete in the United States is fairly recent, there is a lack of expert engineers and contractors required for its special installation.

1.5 Objectives of Present Research

In this thesis, the effects of varying the components of pervious concrete has on its compressive strength are investigated. The goal is to achieve a maximum compressive strength without inhibiting the permeability characteristics of the pervious concrete. This will be accomplished through extensive experiments on test cylinders created for this purpose. Experiments include specific gravity tests, permeability tests, and compression tests.

Loadings on pervious concrete are also an area of concern. Existing pervious concrete pavements are studied. Data drawn from these pavements are utilized along with the results of the compression tests to determine vehicular loadings and volumes that the pervious concrete can sustain over time. Additionally, pavement thickness design will be conducted on varying soil types and loadings.

As with any research, the experiments performed are subject to limitations. These limitations are in regards to the type and size of aggregate used and the curing process. These restrictions are discussed further in more detail.

1.6 Outline of Thesis

1.6.1 Chapter 2.0

Prior to any experiments, research must be conducted on similar areas of studies. Data was gathered on results of previous experiments performed by researchers on compressive strength of pervious concrete. A summary of their results and conclusions are presented in a series of graphs and tables.

In order to achieve the best possible pervious concrete system, the elements that make up the concrete must be analyzed. Water, aggregate, cement, and their corresponding relationships with one another are discussed along with the potential impact each can have on the strength and permeability of pervious concrete.

1.6.2 Chapter 3.0

All good research should be able to be duplicated by another. This chapter will discuss procedures used in experiments conducted for this study. These experiments include specific gravity, permeability, and compressive strength tests. Methods used for determining traffic loadings and volumes on existing pervious concrete systems are also examined. Explanation of calculations for pavement thickness design are also addressed.

1.6.3 Chapter 4.0

Here, an in depth discussion about the results of all experiments is given and also presented in tables and graphs. Comparisons are made between compressive strength and varying ratios of water, cement, and aggregate. Acceptable vehicle types, their loadings, and volumes are also provided. Pavement thickness design tables are provided utilizing the data obtained from experiments.

1.6.4 Chapter 5.0

Conclusions about acceptable ratios, loadings, and pavement thicknesses are drawn from the resulting data obtained from experimentation. Recommendations for future research with pervious concrete and its usage are also given.

2.0 LITERATURE REVIEW

2.1 Previous Studies

To create a pervious concrete structure with optimum permeability and compressive strength, the amount of water, amount of cement, type and size of aggregate, and compaction must all be considered. A multitude of experiments have been previously conducted throughout the past few decades by a variety of researchers comparing some or all of these elements. The results are presented in a series of tables and graphs.

In 1976, V.M. Malhotra discussed pervious concrete as it relates to applications and properties. He provided details on such properties as consistency, proportions of materials, unit weight, compactibility, and curing in an attempt to maximize permeability in the pervious concrete. Malhotra also conducted multiple experiments on various test cylinders in an attempt to find a correlation between compressive strength and any of the material's properties. He concluded that the compressive strength of pervious concrete was dependent on the water cement ratio and the aggregate cement ratio. Table 2.1.1 and Figure 2.1.1 illustrate the relationship between compressive strength and time using various water cement ratios and aggregate cement ratios. He also concluded that even the optimum ratios still would not provide compressive strengths comparable to conventional concrete. Malhotra went on to investigate the effects of compaction on compressive strengths. Table 2.1.2 and Figure 2.1.2 show the correlation between compressive strength and unit weight when different aggregate cement ratios along with various aggregate gradings are employed. Malhotra also experimented on different types of aggregates and their effect on compressive strength. Table 2.1.3 shows the relationship between aggregate type and compressive strengths.

Table 2.1.1 Relationship between Compressive Strength and W/C & A/C Ratios
(Aggregate Size ¾ " Gravel)

Aggregate Cement Ratio (A/C)*	Water Cement Ratio (W/C)**	Age of Test (days)	Density (lb/ft^3)	Cement (lb/yd^3)	Compressive Strength (psi)
6	0.38	3	125.8	436	1295
		7	125.4	436	1660
		28	124.8	436	2080
8	0.41	3	120	326	850
		7	119.5	326	1055
		28	119.4	326	1365
10	0.45	3	116.7	261	625
		7	116.4	261	780
		28	116.2	261	1015

Source: Malhotra (1976),ACI Journal, Vol. 73, Issue 11, p633.
*A/C Ratios are by volume.
**W/C Ratios are by weight.

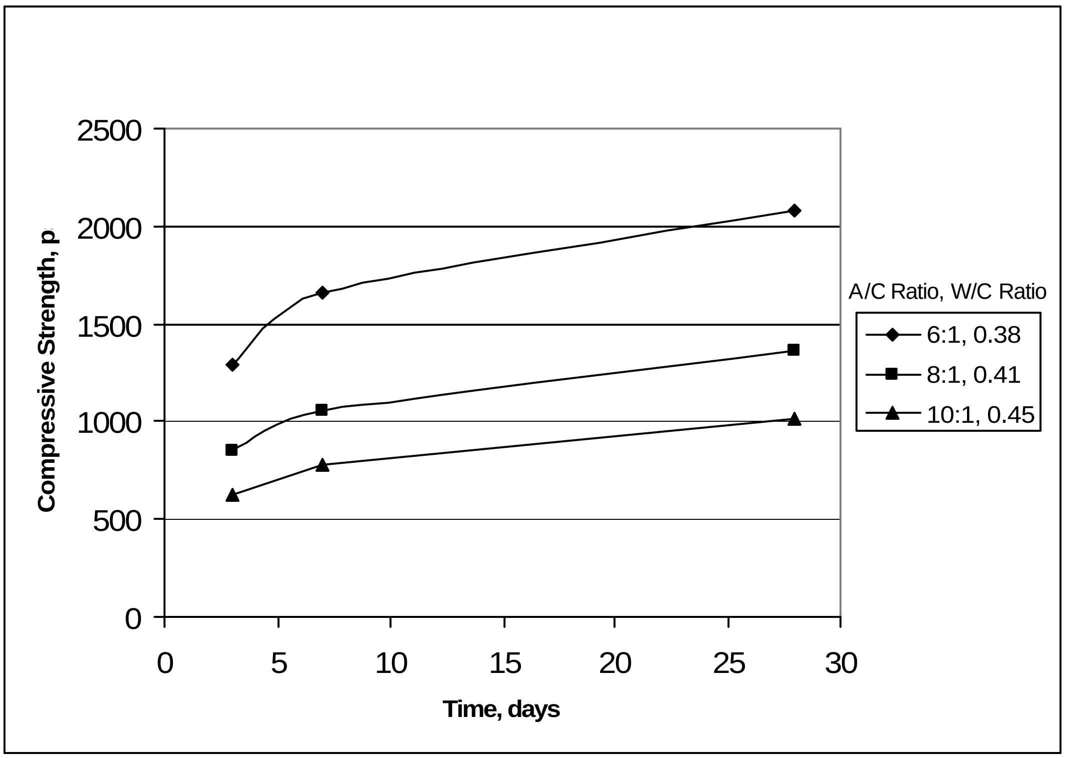


Figure 2.1.1 Compressive Strength vs. Time

Table 2.1.2 Relationship between 28 Day Compressive Strength and Grading
(Water Content = 0.36)

Grading	Aggregate Cement Ratio (A/C) by Volume	Unit Weight (lb/ft^3)	Compressive Strength (psi)
A*	8	119.2	1230
		116.8	975
		116	1090
		113.2	815
B**	9	117.6	1040
		113.6	825
		112.4	745
C***	7	117.2	1280
		115.6	1030
		114	1000
		114	950

* A = minus 3/4 in, plus 3/4 in
** B = minus 3/4 in, plus 1/2 in
*** C = minus 1/2 in, plus 3/8 in
Source: Malhotra (1976), ACI Journal, Vol 73, Issue 11, p634

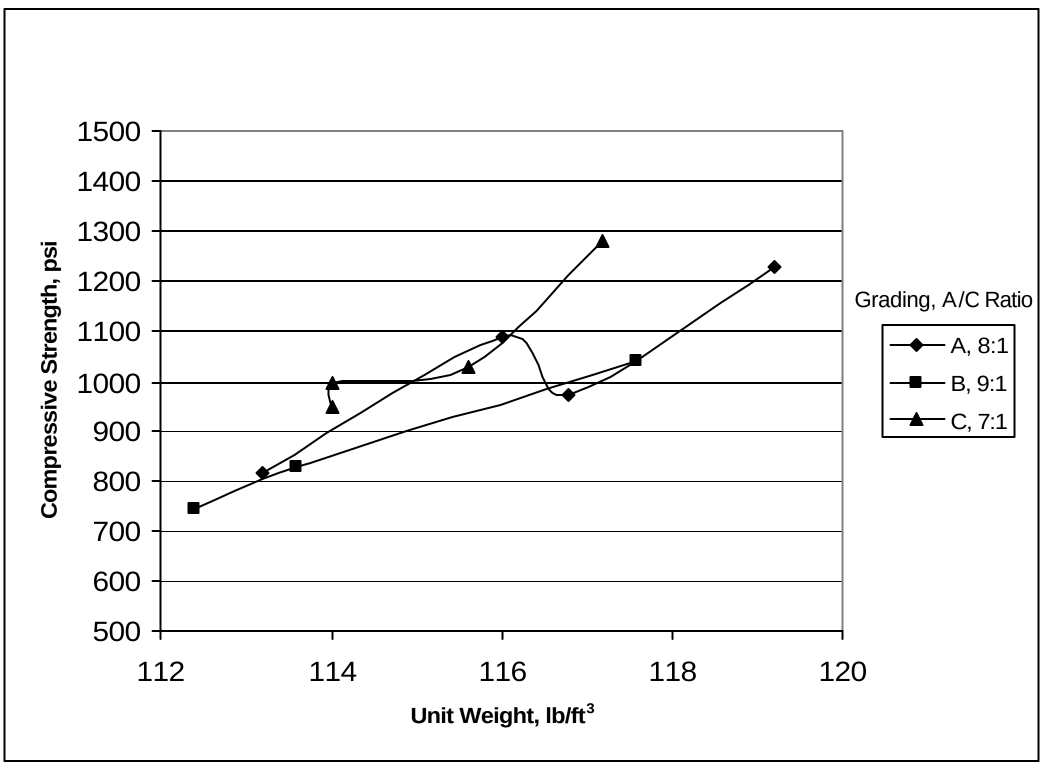


Figure 2.1.2 28 Day Compressive Strength vs. Unit Weight

Table 2.1.3 Relationship between 28 Day Compressive Strength and Aggregate (Water Content = 0.40)

Type of Aggregate	Dry Density (lb/ft^3)	Compressive Strength (psi)
Rounded Quartzite Gravel	115	1250
Irregular Flint Gravel	99	700
Crushed Limestone	114	1000
Crushed Granite	106	1100

Source: Malhotra (1976), ACI Journal, Vol. 73, Issue 11, p634

In 1988, Richard Meininger released results on laboratory experiments he had conducted on pervious concrete. Research was carried out on multiple samples with varying material properties. These properties included water cement ratio, aggregate cement ratio, compaction, and curing time. Results were similar to those found by Malhotra in 1976. Meininger discovered a relationship between the 28 day compressive strength and water content while utilizing aggregate 3/8" in size and an aggregate cement ratio equal to 6. This relationship is seen in Table 2.1.4 and Figure 2.1.3. Meininger then investigated the correlation between the 28 day compressive strength and unit weight. This association is shown in Table 2.1.5 and Figure 2.1.4. Lastly Meininger once again studied the relationship between 28 day compressive strength and water content ratio but altered aggregate cement ratio and aggregate size. The results are seen in Table 2.1.6 and Figure 2.1.5. The results of these experiments led Meininger to deduce an optimum water cement ratio that would maximize water permeability but not necessarily maximize compressive strength. Meininger also determined that pervious concrete provided a lower compressive strength than that of conventional concrete and should only be utilized in areas restricted to automobile use or light duty areas.

Meininger went on to study the relationship between air content and compressive strength. As expected, an increase in air content decreases the compressive strength of concrete. This occurs because the space once occupied by aggregate now contains air thereby reducing the structural material in the concrete. This result is presented graphically in Figure 2.1.6.

Table 2.1.4 Relationship between 28 Day Compressive Strength and Water Content

(3/8" Coarse Aggregate – Aggregate/Cement Ratio = 6)

Water Content (by weight)	28 Day Compressive Strength (psi)	Cement (lb/yd^3)	Water (lb/yd^3)	Aggregate (lb/yd^3)	Air (%)	Permeability (in.min)
0.51	1350	440	224	2640	22	5
0.47	1370	430	203	2575	23	4
0.43	1500	430	184	2570	25	10
0.39	1400	425	165	2550	27	30
0.35	1250	415	145	2520	29	40
0.31	1010	410	125	2430	32	51
0.27	870	395	106	2370	33	59

Source: Meininger (1988), Concrete International, Vol 10, Issue 8, p22

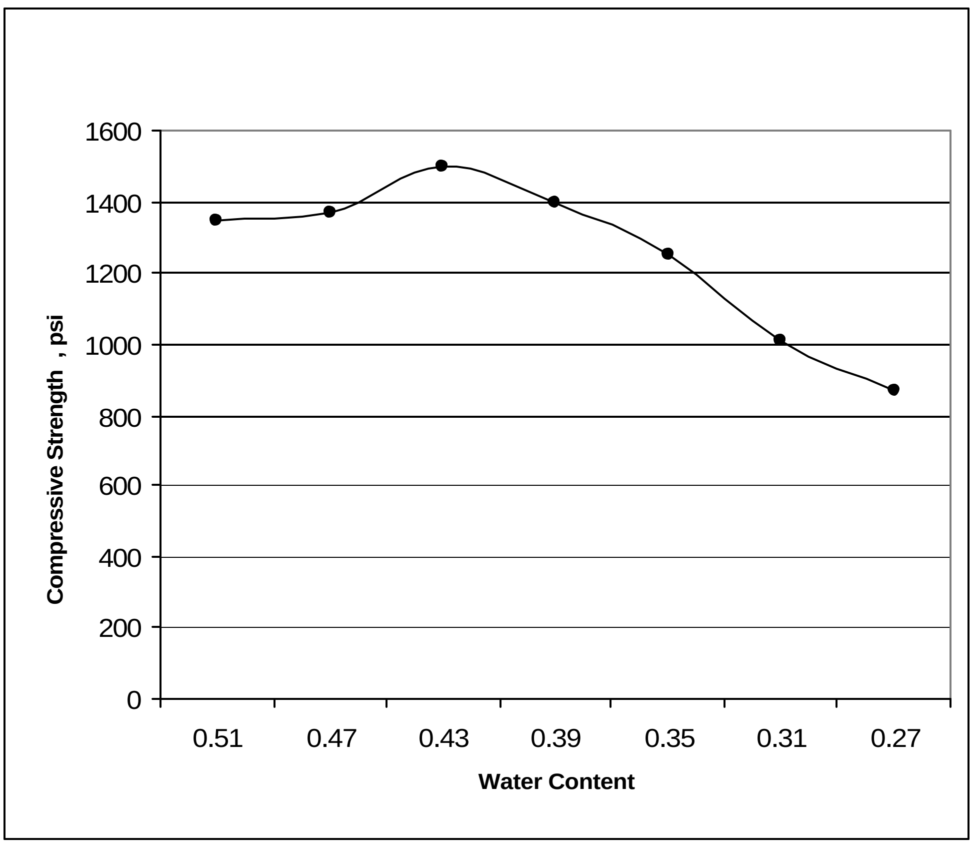


Figure 2.1.3 28 Day Compressive Strength vs. Water Content

Table 2.1.5 Relationship between 28 Day Compressive Strength and Unit Weight

Water Content Ratio (by weight)	Unit Weight (lb/ft^3)	Compressive Strength (psi)	Water Content Ratio (by weight)	Unit Weight (lb/ft^3)	Compressive Strength (psi)
0.34	111	1355	0.31	107.5	975
	110.5	1340		107.5	1050
	112.5	1360		110	1100
	114	1550		112	1395
	120.8	1945		118	1540
	122	2475		120.5	2095

Source: Meininger (1988), Concrete International, Vol. 10, Issue 8, p21

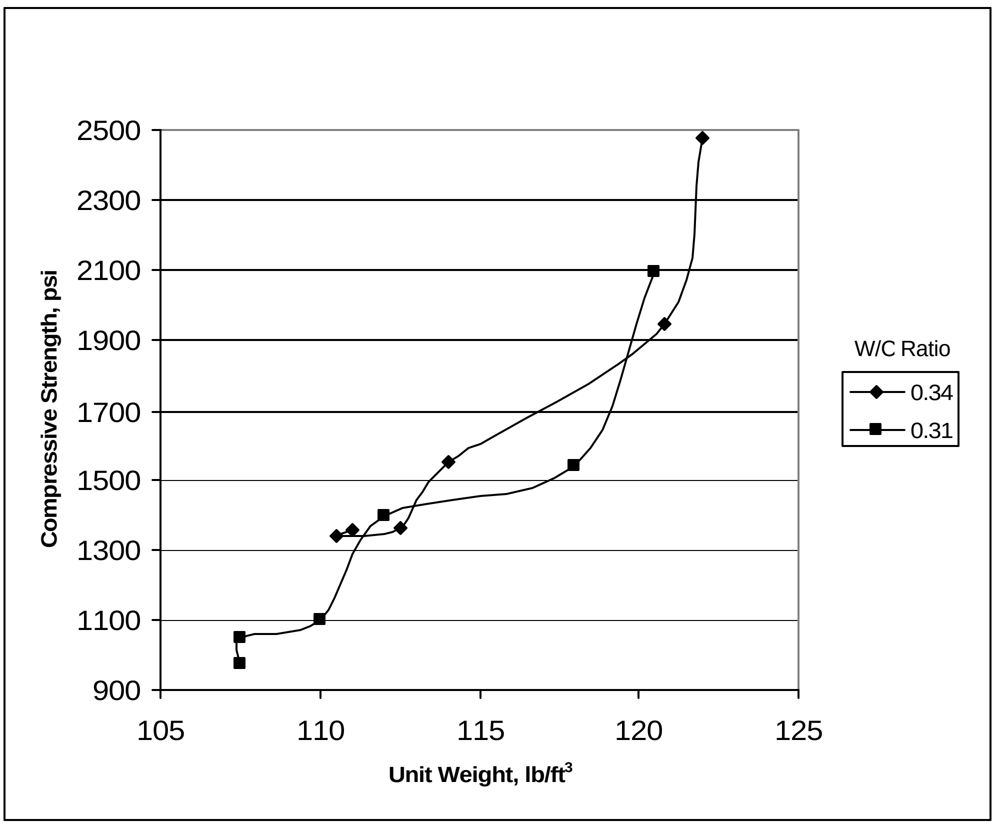


Figure 2.1.4 28 Day Compressive Strength vs. Unit Weight

Table 2.1.6 Relationship between 28 Day Compressive Strength and W/C Ratio

Aggregate Cement Ratio	Aggregate Size	Water Cement Ratio	Compressive Strength (psi)	Aggregate Cement Ratio	Aggregate Size	Water Cement Ratio	Compressive Strength (psi)
10	3/4"	0.27	625	6	3/8"	0.27	1100
		0.35	750			0.31	1250
		0.42	800			0.35	1400
		0.51	775			0.39	1800
						0.43	1650
6	3/4"	0.25	775			0.47	1400
		0.33	1150			0.51	1700
		0.37	1400	4	3/4"	0.25	900
		0.41	1250			0.33	1950
		0.49	1050			0.41	2050
						0.49	2200

Source: Meininger (1988), Concrete International, Vol. 10, Issue 8, p22

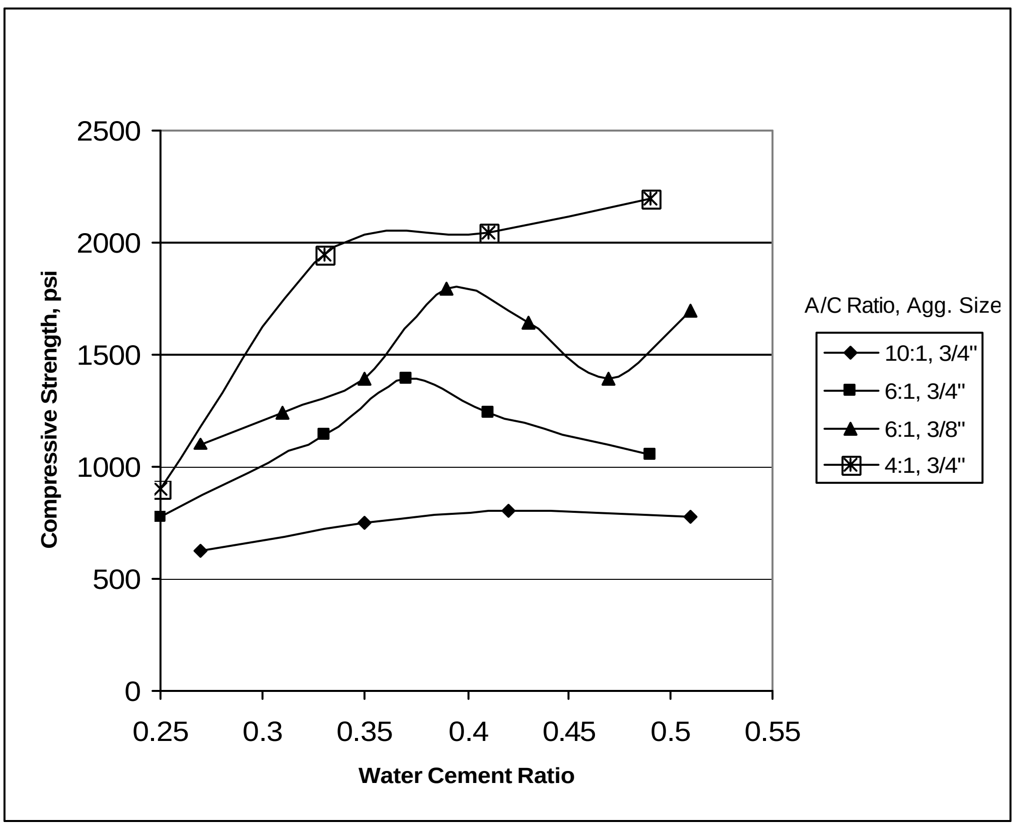


Figure 2.1.5 28 Day Compressive Strength vs. W/C Ratio

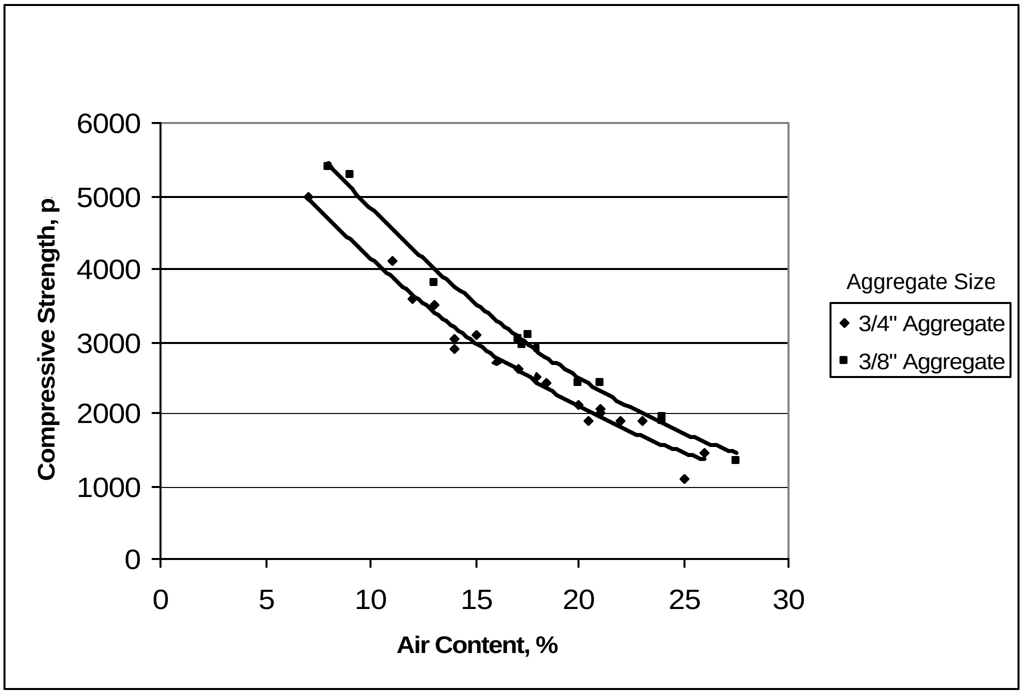


Figure 2.1.6 Compressive Strength vs Air Content

In 1995 extensive research was conducted by Nader Ghafoori on various aspects of pervious concrete. In one study, he investigated various sites throughout the United States that have utilized pervious concrete paving systems. His investigation led to a comparison of compressive strength attained at each of these sites. He also examined failures in the various pavements if any had occurred along with the water cement and aggregate cement ratios. Next, Ghafoori inspected applications of pervious concrete outside the United States and once again compared the compressive strengths.

Ghafoori also discusses, in detail, pavement thickness design for pervious concrete. He deduces that compressive strength depends on the water cement ratio, the aggregate cement ratio, compaction, and curing. He also provides a chart which displays the effects of varying the aggregate cement ratio and compaction energy have on the compressive strength and permeability. These results are shown in Table 2.1.7 and Figure 2.1.7.

Table 2.1.7 Relationship between Compressive Strength and A/C Ratios

A/C Ratio	Water Content	Compaction Energy (kN-m/m^3)	Permeability (in/min)	Strength (psi)
4	0.372	0.013	215	1650
		0.033	125	2200
		0.066	65	2850
		0.099	60	3300
		0.132	55	3500
		0.165	30	4000
		0.198	20	4200
		0.264	15	4500
4.5	0.381	0.013	220	1450
		0.033	140	2000
		0.066	115	2300
		0.099	110	2500
		0.132	70	2700
		0.165	60	3000
		0.198	55	3200
		0.264	50	3550

Source: Ghafoori (1995), Journal of Transportation Engineering, Vol. 121, No. 6, p477

A/C Ratio	Water Content	Compaction Energy (kN-m/m^3)	Permeability (in/min)	Strength (psi)
5	0.39	0.013	230	1250
		0.033	210	1800
		0.066	150	2100
		0.099	135	2300
		0.132	115	2400
		0.165	100	2500
		0.198	75	2700
		0.264	60	3000
6	0.418	0.013	240	1100
		0.033	210	1700
		0.066	190	2000
		0.099	150	2100
		0.132	150	2200
		0.165	130	2300
		0.198	120	2400
		0.264	100	2600

Source: Ghafoori (1995), Journal of Transportation Engineering, Vol. 121, No. 6, p477

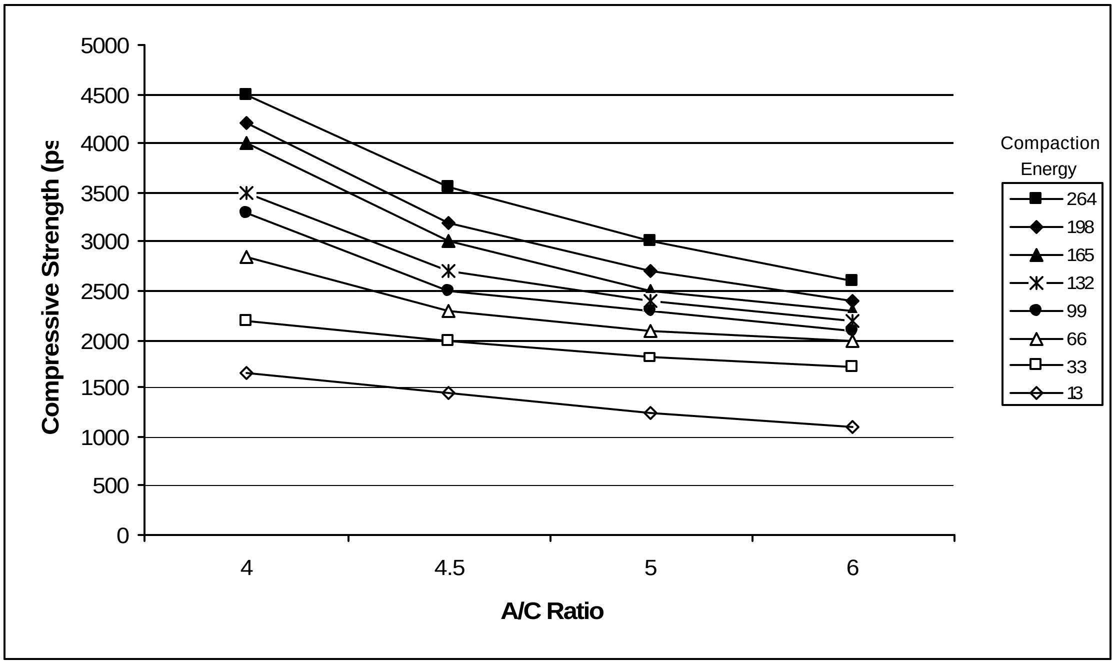


Figure 2.1.7 28 Day Compressive Strength vs. A/C Ratio

Ghafoori conducts extensive laboratory experiments on four different samples of pervious concrete to determine relationships between compressive strength and multiple variables such as curing, water cement ratio, aggregate cement ratio, and compaction. The samples had varying water cement ratios and aggregate cement ratios. The conclusions drawn as a result of these experiments indicated pervious concrete is comparable to conventional concrete when considering shrinkage and depth of wear. Of interesting note is Ghafoori claims that under the right circumstances, proper proportioning of materials and correct compaction, pervious concrete can attain compressive strengths of 3000 psi. This directly contradicts the findings of other researchers.

Finally, Ghafoori utilized the data he had obtained from his experiments on pervious concrete and determined appropriate thickness levels for varying soil subgrades and moduli of rupture. His calculations are based on different traffic categories. These categories are provided in Table 2.1.8.

Table 2.1.8 Traffic Categories

Vehicle Type	Use	Category
Car	Parking area and access lane	A
Truck	Access lane	A-1
	Shopping center entrance and service lanes	B
Bus	Parking area and exterior lanes	B
Bus	Entrance and exterior lanes	C
Single-unit truck	Parking area and interior lanes	B
Single-unit truck	Entrance and exterior lanes	C
Multiunit truck	Parking area and interior lanes	C
Multiunit truck	Entrance and exterior lanes	D

Source: Ghafoori (1995), Journal of Transportation Engineering, p 480.

He went on to calculate thicknesses based on the AASHTO method and the PCA method. These results are presented in Table 2.1.9 and Table 2.1.10.

Table 2.1.9 Thickness Design by AASHTO Method

Modulus of rupture (psi)	Traffic Category							
	A(1)	A(10)	B(25)	B(300)	C(100)	C(300)	C(700)	D(700)
k = 500 pci								
600	3.5	3.5	3.5	4.0	3.5	3.5	5.5	9.5
550	3.5	3.5	3.5	4.2	3.5	3.5	5.8	9.9
500	3.5	3.5	3.5	4.5	3.5	4.0	6.0	10.0
450	3.5	3.5	3.5	5.0	3.5	4.5	6.4	11.0
k = 400 pci								
600	3.5	3.5	3.5	4.7	3.5	4.6	5.9	9.7
550	3.5	3.5	3.5	4.9	3.5	4.7	6.1	10.0
500	3.5	3.5	3.5	5.0	3.5	4.8	6.4	11.0
450	3.5	3.5	3.5	5.4	3.5	5.2	6.8	11.0
k = 300 pci								
600	3.5	3.5	3.5	5.2	3.5	5.0	6.2	9.9
550	3.5	3.5	4.0	5.4	3.5	5.2	6.5	10.0
500	3.5	3.5	4.1	5.6	3.5	5.5	6.8	11.0
450	3.5	3.5	4.5	5.9	3.5	5.8	7.2	11.0
k = 200 pci								
600	3.5	3.5	3.5	5.6	4.1	5.5	6.6	10.0
550	3.5	3.5	3.5	5.8	4.2	5.7	6.9	11.0
500	3.5	3.5	3.5	6.0	4.3	5.9	7.2	11.0
450	3.5	3.5	3.5	6.4	4.5	6.3	7.6	12.0
k = 100 pci								
600	3.5	3.5	3.5	6.0	4.6	5.9	7.0	11.0
550	3.5	3.5	3.5	6.3	4.8	6.1	7.3	11.0
500	3.5	3.5	3.7	6.6	5.0	6.4	7.6	12.0
450	3.5	3.5	3.9	7.0	5.3	6.8	8.0	12.0
k = 50 pci								
600	3.5	3.5	3.8	6.4	5.0	6.2	7.3	10.0
550	3.5	3.5	4.0	6.6	5.2	6.5	7.6	11.0
500	3.5	3.5	4.1	6.9	5.4	6.8	8.0	12.0
450	3.5	4.0	4.4	7.3	5.7	7.2	8.4	13.0

Source: Ghafoori (1995), Journal of Transportation Engineering, p 482.

Table 2.1.10 Thickness Design by PCA Method

Modulus of rupture (psi)	Traffic Category							
	A(1)	A(10)	B(25)	B(300)	C(100)	C(300)	C(700)	D(700)
k = 500 pci								
600	3.5	4.0	4.5	5.0	5.0	5.5	5.5	6.5
550	4.0	4.0	4.5	5.0	5.5	5.5	6.0	6.5
500	4.0	4.5	5.0	5.5	6.0	6.0	6.0	6.5
450	4.5	5.0	5.5	6.0	6.5	6.5	7.0	6.5
k = 400 pci								
600	3.5	4.0	4.5	5.0	5.0	5.5	5.5	6.5
550	4.0	4.5	5.0	5.5	5.5	6.0	6.0	6.5
500	4.0	4.5	5.5	6.0	6.0	6.0	6.5	6.5
450	4.5	5.0	5.5	6.5	6.5	6.5	7.0	6.5
k = 300 pci								
600	3.5	4.0	5.0	5.5	5.5	5.5	6.0	6.5
550	4.0	4.5	5.0	5.5	5.5	6.0	6.0	6.5
500	4.5	4.5	5.5	6.0	6.0	6.5	6.5	6.5
450	4.5	5.0	6.0	6.5	6.5	7.0	7.0	7.0
k = 200 pci								
600	4.0	4.5	5.0	5.5	5.5	6.0	6.0	7.0
550	4.5	4.5	5.5	6.0	6.0	6.5	6.5	7.0
500	4.5	5.0	6.0	6.5	6.5	7.0	7.0	7.0
450	5.0	5.5	6.0	7.0	7.0	7.5	7.5	7.0
k = 100 pci								
600	4.5	5.0	5.5	6.0	6.0	6.5	6.5	8.0
550	4.5	5.0	6.0	6.5	6.5	7.0	7.0	8.0
500	5.0	5.5	6.5	7.0	7.0	7.5	7.5	8.0
450	5.5	6.0	7.0	7.5	7.5	8.0	8.0	8.0
k = 50 pci								
600	5.0	5.5	6.0	6.5	7.0	7.0	7.5	9.0
550	5.0	5.5	6.5	7.0	7.5	7.5	8.0	9.0
500	5.5	6.0	7.0	7.5	8.0	8.0	8.5	9.0
450	6.0	6.5	7.5	8.0	8.5	8.5	9.0	9.0

Source: Ghafoori (1995), Journal of Transportation Engineering, p 483.

In 2003, Paul Klieger performed experiments studying the effects of entrained air on the strength and durability of conventional concrete. Although never utilizing the amount of voids seen in pervious concrete (15%-35%), his research clearly shows the impact the presence of air has on the performance of concrete. He concluded that the reduction in compressive strength with the presence of air decreases as the size of aggregate decreases and as the cement content decreases. These are both due to the reduction in water. Graphical representations of his findings are shown in Figures 2.1.8, 2.1.9, and 2.1.10.

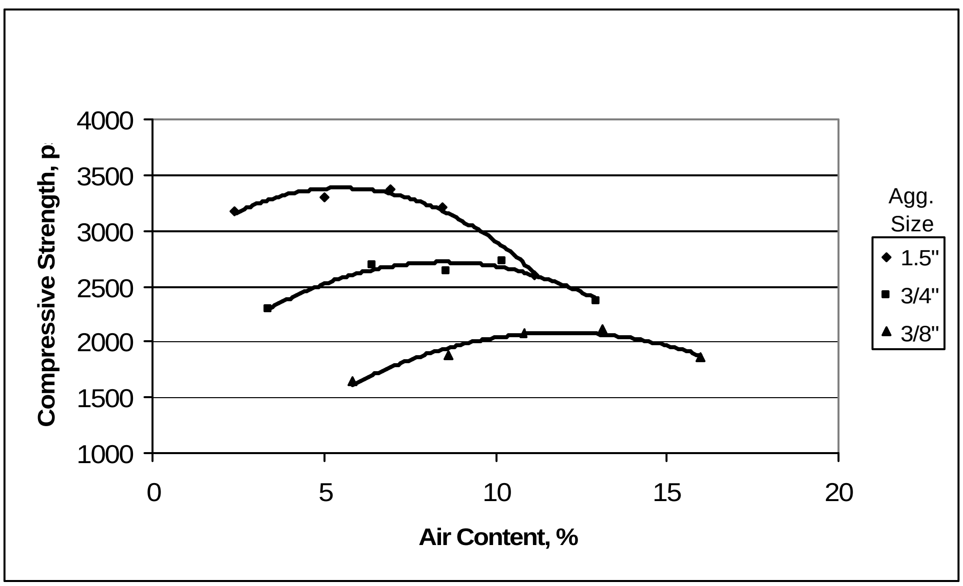


Figure 2.1.8 Compressive Strength vs Air Content – 4 sacks Cement

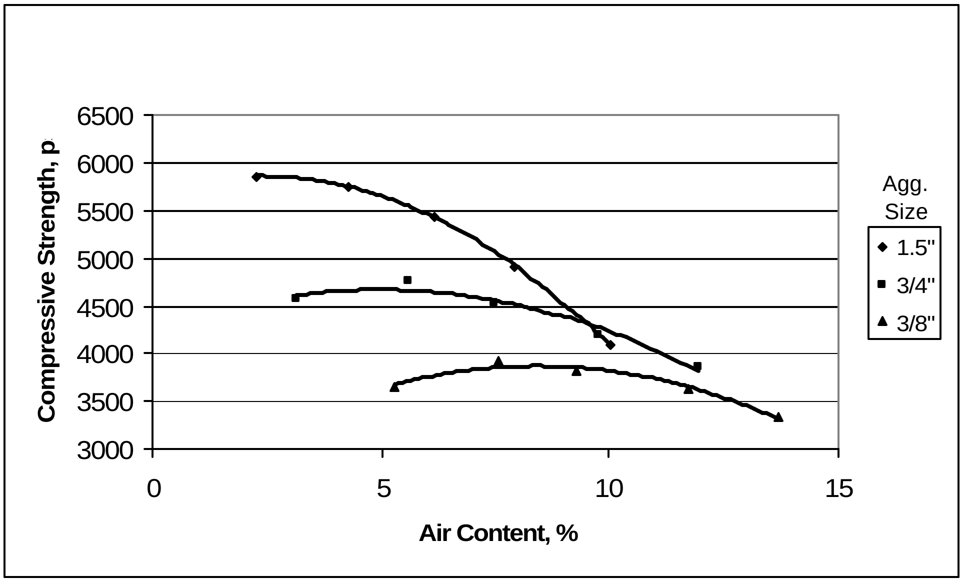


Figure 2.1.9 Compressive Strength vs Air Content – 5.5 sacks Cement

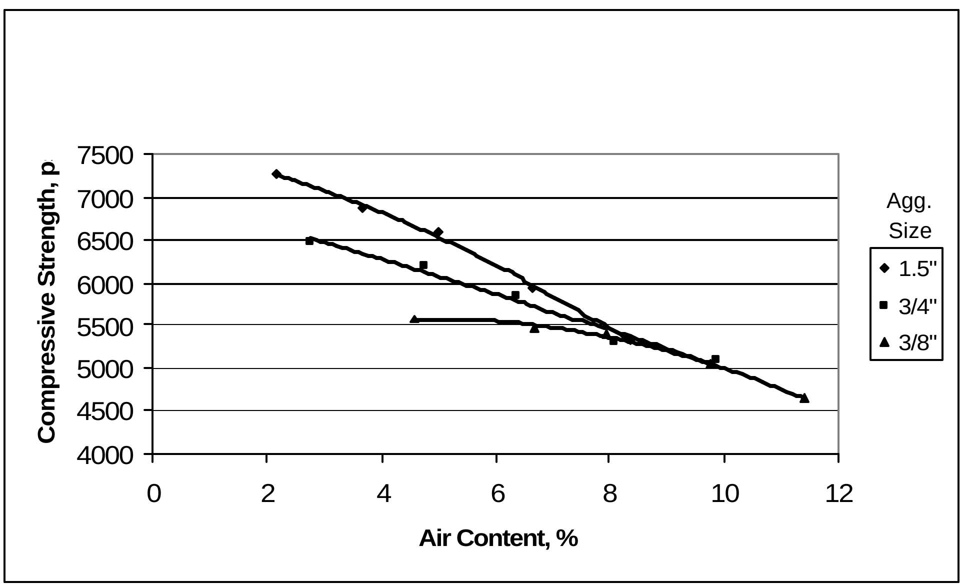


Figure 2.1.10 Compressive Strength vs Air Content – 7 sacks Cement

Research conducted in the past 30 years has drawn similar conclusions. The compressive strength of pervious concrete is strongly dependent on the water cement ratio, the aggregate cement ratio, aggregate size, compaction, and curing. Experiments also indicate that pervious concrete is most beneficial and should be restricted to areas subjected to low traffic volumes. Researchers disagree as to whether pervious concrete can consistently attain compressive strengths equal to conventional concrete.

2.2 Water

Just as water is the source of life for all living things it is the primary ingredient for the beginning of all concrete. Without water or too little water, all that exists is a pile of rocks and powder. The opposite can also adversely affect the development of concrete. Too much water and concrete will become a soupy mixture resembling clam chowder rather than a functional structural material.

Water is imperative for two reasons. One is to hydrate the cement and the second is to create a workable substance. Hydration of the cement is necessary to form bonds with the aggregate which in turn give concrete its strength. Conversely the presence of water filled spaces within the concrete is detrimental to its strength. Indications are that concrete strength is directly related to porosity and the water-cement ratio (W/C). This is shown by the hydration process. As hydration of cement progresses, the volume of solids increases. This volume is in the space previously occupied by the unhydrated cement. The increase in solids volume indicates a decrease in porosity.

Porosity affects strength but strength itself is a result of bonding. Developing bonds in mixtures with high W/C ratios is difficult due to the distances between particles. A high W/C ratio means a mixture with a high porosity. Therefore a high porosity means weaker bonds which in turn lead to lower strength.

The amount of water required to complete hydration and achieve maximum strength has long been debated. As previously discussed, the strength in concrete is developed through bonds. These bonds develop through a chemical reaction of cement and water. This reaction produces calcium silicate hydrate. One gram of cement requires 0.22 grams of water in order to fully hydrate. However, the volume of the products of hydration is greater than the volume of cement and water used in the reaction. Specifically, it requires a volume of 1.2 mL of water for the products of hydration for 1mL of cement. This equates to a W/C ratio of 0.42 for complete hydration (Aitcin and Neville, 2003).

As noted previously, some of the water is required for workability of the concrete. This added water is needed because of flocculation that occurs to the particles of cement. This floc decreases workability and impedes hydration. It is possible to include admixtures which eliminate flocculation. Water once used to counteract this effect is now used for hydration, thereby reducing the amount of water needed.

Water and its application in pervious concrete are extremely critical. Since fines are eliminated from pervious concrete, strength relies on the bond of the cement paste and its interface with the aggregate. As with conventional concrete, too little water results in no bonding and too much water will settle the paste at the base of the pavement and clog the pores. The correct amount of water will maximize the strength without compromising the permeability characteristics of the pervious concrete.

The concepts of hydration and workability will be considered when creating mixtures of pervious concrete with varying ratios of cement, aggregate, and water. Water will be added to various mixtures of aggregate and cement in experiments designed to maximize hydration and optimize compressive strength. The goal is to determine an appropriate range of W/C ratios that will yield high compressive strengths in the pervious concrete.

2.3 Aggregate Type and Size

Generally the strength of aggregate is not considered when discussing the strength of concrete. Failure of concrete specimens in a compression test usually occurs at the aggregate-paste interface. This proves the adage “You are only as strong as your weakest link.” This demonstrates that the bond strength is weaker than both the strength of the paste and the strength of the aggregate. All indications are that the strength of the concrete is dictated by the strength of the bond and not the individual components.

However, in pervious concrete the cement paste is limited and the aggregate rely on the contact surfaces between one another for strength. Therefore harder aggregate, such as granite or quartz, would yield higher compression strength than a softer aggregate like limestone.

Typically aggregate within the range of 3/8" and 3/4" are used because of enhanced handling and placement. Anything larger would result in larger void spaces but would provide a rougher surface.

Aggregate supplied for this study is limited to 3/8". The type of aggregate used is limestone and it's specific gravity will be found through experiments conducted on the rock later in the study.

2.4 Aggregate-Cement Ratio

The amount of aggregate relative to the amount of cement is another important feature. The more cement paste available for compaction the higher the compressive strength. Again this will clog the pores and is detrimental to the function of the pervious concrete.

Utilizing data obtained from prior research, a suitable range of A/C ratios will be used to create various mixtures of pervious concrete to be tested for compressive strength.

2.5 Compaction

The amount of compaction can have considerable effects on the function of pervious concrete. A higher degree of compaction that takes place when the concrete is placed will directly lead to a higher level of strength in the concrete. This is due to the densification of the concrete and the elimination of voids. These are the same voids necessary for the permeability of the water. Too much compaction will therefore result in a loss of permeability through the concrete and a failure of the pervious concrete system.

Prior experiments conducted by other researchers on pervious concrete utilized various techniques for compaction such as rollers, hand tamping, and Proctor tests. In order to quantify the amount of compaction applied to each of the test cylinders, the standard and modified Proctor compaction tests were used.

2.6 Soil Type

One of the factors that pavement thickness is dependent on is the modulus of subgrade reaction,k, or the type of soil beneath the concrete. Research on different types of soils provided information of various soils and their corresponding k values. These soil types and values are provided in Table 2.6.1, Table 2.6.2, and Table 2.6.3.

Table 2.6.1 Subgrade Soil Types and Approximate k Values

Type of Soil	Support	k Values (pci)
Fine-grained soils in which silt and clay-size particles predominate	Low	75-120
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130-170
Sands and sand-gravel mixtures relatively free of plastic fines	High	180-220
Cement-treated subbases	Very High	250-400

Source: Huang (2004), Pavement Analysis and Design, p.564.

Table 2.6.2 AASHTO Soil Classification

Class	Soil Type	Subgrade Rating	k Value (pci)
A-1-a	Stone fragments, gravel, and sand	Excellent to Good	400-710
A-1-b	Stone fragments, gravel, and sand	Excellent to Good	250-590
A-2-4	Silty or clayey gravel and sand	Excellent to Good	290-710
A-2-5	Silty or clayey gravel and sand	Excellent to Good	290-710
A-2-6	Silty or clayey gravel and sand	Excellent to Good	180-340
A-2-7	Silty or clayey gravel and sand	Excellent to Good	180-340
A-3	Fine Sand	Excellent to Good	200-340
A-4	Silty Soils	Fair to Poor	100-300
A-5	Silty Soils	Fair to Poor	50-180
A-6	Clayey Soils	Fair to Poor	50-220
A-7-5	Clayey Soils	Fair to Poor	50-220
A-7-6	Clayey Soils	Fair to Poor	50-220

Sources: Huang (2004), Pavement Analysis and Design, p.328.
Das (2002), Principles of Geotechinical Engineering, p. 84.

Table 2.6.3 ASTM Soil Classification

Class	Soil Type	k Value (pci)
GP	Poorly graded gravel	290-590
GW	Well-graded gravel	590-710
GM	Silty gravel	250-710
GC	Clayey gravel	250-420
SW	Well-graded sand	250-420
SM	Silty sand	200-420
SP	Poorly graded sand	200-290
SC	Clayey sand	200-250
ML	Silt gravel or sand	140-230
MH	Elastic silt with gravel or sand	120-180
CL	Lean clay with gravel or sand	140-230
CH	Fat clay with gravel or sand	100-140
OL	Organic clay or silt with gravel or sand	120-180
OH	Organic clay or silt with gravel or sand	100-140

Sources: Huang (2004), Pavement Analysis and Design, p.328.
Das (2002), Principles of Geotechinical Engineering, p. 85-91.

3.0 METHODOLOGY

3.1 Introduction

In this chapter focus on the procedures utilized for creating and testing pervious concrete is done. To draw reasonable conclusions in regards to choosing appropriate mixture ratios for pervious concrete, testing and experimentation must be conducted. Compressive strength is best determined by creating pervious concrete and subjecting it to loadings until failure.

Traffic loadings and volumes of future sites will be determined by evaluating existing sites with similar characteristics. Precise traffic counts of these existing sites are the most accurate for developing this data. Due to time constraints, however, traffic counts were not feasible for this study. Transportation charts were used to make estimates of traffic volumes and loadings.

3.2 Specific Gravity and Unit Weight of the Aggregate

The A/C ratio is by volume and not by weight. The unit weight of the aggregate was required for calculating correct volumes for the ratio. Unit weight was obtained by conducting specific gravity tests. Two experiments were conducted in accordance with ASTM C29/29M-97. A quantity of aggregate was obtained, oven dried, and its weight recorded (W3). A container was then filled with water up to a certain level, weighed, and its weight recorded (W1). The water was then emptied from the container and replaced by the aggregate. Water was then reintroduced into the container until the previous level was reached. The container with the water and the aggregate was then weighed (W2). The mass of aggregate equal to the volume of water removed from the container (W4) is then determined by adding W1 and W3 and subtracting W2. Specific gravity is then calculated by dividing W3 by W4.

3.3 Cylinders used for Testing

Although much research has been conducted in the past on its compressive strength, testing must still be accomplished in order to understand the nature of pervious concrete. Prior research is an excellent source, however, to develop parameters for that testing. Based on prior readings, thirty-two (32) test cylinders would provide a representative sample of varying mixture ratios (i.e. A/C ratio and W/C ratio). The cylinders used for testing were one time use only. These cylinders are four inches in diameter and eight inches in height. The pervious concrete was made from 3/8 inch aggregate and Type I Portland Cement. The test cylinders used and the pervious concrete mixed are in accordance with ASTM C31/C31M-03a. Eight separate batches with four different A/C ratios and two methods of compaction (Standard Proctor and Modified Proctor) were created. The Standard Proctor compaction test requires test cylinders be filled in three layers. Each layer receives twenty-five blows with a hammer weighing 5.5 lbs through a distance of twelve inches. The Modified Proctor compaction test requires test cylinders be filled in five layers. Each layer also receives twenty-five blows with a hammer, however, this hammer weighs 10 lbs and is dropped a distance of eighteen inches. The Standard Proctor compaction test provided 341 kN-m/m^3 of energy or 50 psi of vertical force while the Modified Proctor compaction test provided 1544 kN-m/m^3 of energy or 223 psi of vertical force. See Appendix A for calculations.

The W/C ratio is not required for the mixture parameters and is calculated after completion of the mixture. Since water is added to the aggregate and cement until a sheen is developed throughout the mix, it is impossible to have this value prior to mixing. The amount of water utilized is converted to weight and divided by the amount of cement used by weight to calculate the W/C ratio used for each mixture.

Once the unit weight of the aggregate is calculated, correct volumes of aggregate and cement are determined for mixing. Each mixture provided enough pervious concrete for four cylinders with the exception of Mixture 4. In this batch, an incorrect amount of aggregate is used thereby affecting the amount of pervious concrete produced. The amount of pervious concrete created yielded enough for only three cylinders. Four cylinders per mixture allowed for two cylinders with identical parameters (A/C ratio, W/C ratio, and compaction energy). Table 3.3.1 provides a breakdown of each mixture and its corresponding parameters.

Table 3.3.1 Mixtures and Corresponding Parameters

Mix	No.	Water Cement Ratio (by weight)	Aggregate Cement Ratio (by Volume)	Aggregate Content (lb/yd^3)	Cement Content (lb/yd^3)	Water Content (lb/yd^3)
1	1111	0.52	4.00	2488	622	454
	1112					
	1121					
	1122					
2	2111	0.39	4.00	2488	622	343
	2112					
	2121					
	2122					
3	3211	0.44	5.00	2488	498	285
	3212					
	3221					
	3222					
4	4211	0.35	4.00	2488	622	286
	4212					
	4221					
	4222	---Void---	---Error---	---Void---	--Error--	---Void---
5	5311	0.33	6.00	2488	415	172
	5312					
	5321					
	5322					
6	6311	0.38	6.00	2488	415	200
	6312					
	6321					
	6322					
7	7411	0.32	7.00	2488	355	143
	7412					
	7421					
	7422					
8	8411	0.39	7.00	2488	355	171
	8412					
	8421					
	8422					

The cylinders were filled with pervious concrete and immediately upon completion of leveling the surface, each cylinder was covered with 6 mil thick polyethylene plastic for proper curing. The cylinders were left in this condition for seven days.

After seven days, the molds were removed from sixteen (16) of the cylinders. These sixteen cylinders were then wrapped in the 6 mil thick plastic. The bottoms of the remaining fifteen (15) cylinders were removed and covered with the 6 mil plastic. These fifteen cylinders were left within the confines of the mold for future permeability testing. The cylinders remained in this state for an additional three weeks. After a total of 28 days, the plastic was removed from all cylinders and each cylinder was weighed. Permeability experiments were then performed on the fifteen cylinders and specific gravity tests were performed on all thirty-one cylinders. Curing of all the pervious concrete was limited to outside conditions.

There are no standard methods for determining the consistency of pervious concrete. Standard slump tests would provide no slump or very little slump due to the consistency of the material and are therefore not used (Malhotra, 1976 and Ghafoori, 1995). Visual inspection of the concrete seems to be the measure by which consistency is measured. All aggregate should be covered with cement and water until a sheen is developed.

3.4 Permeability, Specific Gravity, and Compressive Strength of Pervious Concrete

Each of the fifteen cylinders was suspended above the ground surface twelve inches in order to allow for the free flow of water. A hose provided a constant flow into the cylinder in order to maintain a head four inches above the surface of the pervious concrete. Once a constant flow was established, a container below the cylinder was able to capture the amount of water flowing through the concrete for a period of one minute. After completion of the permeability tests, specific gravity experiments were conducted on each cylinder in a manner similar to those previously performed on the aggregate in order to determine unit weight, void ratio, and porosity.

Lastly, the 30 day compressive strength was determined on each cylinder using the SATEC Universal Testing Machine with 250 kip capacity. Each cylinder was equipped with a neoprene cap on its top and base and was loaded at a rate of 50 psi/sec until failure. Data was recorded in the form of load in pounds and displacement in inches. This data was then interpreted in the form of graphs.

3.5 Site Investigation of Existing Systems

To determine the longevity of pervious concrete paving systems, it is necessary to investigate current parking areas utilizing pervious concrete. Five sites in the Central Florida area were examined for signs of wear and areas of failure. The type of traffic as well as the number of vehicles each of these areas is subjected to is another area of concern. On-site investigations were performed to locate areas in the paving surfaces that have failed. The Trip Generation Manual was utilized to estimate the amount of traffic each of these areas is subjected to based on the type of business.

3.6 Design Vehicles

Vehicles taken into consideration when designing roadways are referred to as design vehicles. The weight and dimensions of those vehicles expected to use the roadway are required in order to ensure a proper design. After completion of the experiments and after all of the data is analyzed, it is necessary to study what types of vehicles the pervious concrete will be able to sustain over a long period of time without suffering significant damage. Design vehicles defined by AASHTO and vehicle manufacturers will be considered for the purposes of this study.

3.7 Pavement Thickness Design

Pavement thickness design is dependent on many variables. These include but are not limited to the traffic volume, traffic load, drainage, quality of the subgrade, and strength of the pervious concrete. This study will utilize the AASHTO method for determining appropriate thickness levels for various traffic volumes, loadings, and subgrades.

The first step in calculating thickness levels is to determine the amount and type of traffic to travel on the pavement and equate that to the ESAL or equivalent single axle load. The ESAL equates the loads of all vehicles traveling on the roadway to a standard measurement, an 18-kip single axle load. It is given by the following equation:

$$ESAL = (ADT)(T)(T_f)(GY)(D)(L)(365)$$

where ADT = Average Daily Traffic

T = Percentage of Trucks

T_f = Truck Factor

GY = Total Growth Factor

D = Directional Factor

L = Lane Distribution

For this study the average daily traffic will be varied from 500 to 3500 in increments of 250. The percentage of trucks will also vary, ranging from 5% to 20%. The total growth factor is based on a life span of 20 years and a growth rate of 4%. This number is obtained from a chart provided in Appendix D and results in a factor of 29.78. The directional factor and lane distribution are concerned with the number of lanes in each direction. Considering these calculations are for a parking lot, it is assumed that it is one directional and all vehicles enter and exit over relatively the same pavement. Therefore these values are 100% or 1 for calculation purposes.

Once these variables are determined and the ESAL is calculated the thickness of the pavement is determined by AASHTO's 1993 equation for thickness design.

$$\log W = Z_R S_o + 7.35\log(D+1) - 0.06 + \frac{\log[\Delta PSI/(4.5-1.5)]}{1+1.624x10^7/(D+1)^{8.46}}$$

$$+(4.22-0.32p_t)\log\{\frac{S_c C_d(D^{0.75}-1.132)}{215.63[D^{0.75}-18.42/(E_C/k)^{0.25}]}\}$$

where Z = Standard Deviate

S_o = Standard Deviation

E_c = Elastic Modulus of Concrete

k = Modulus of Subgrade Reaction

S_c = Modulus of Rupture of Concrete

C_d = Drainage Coefficient

W = ESAL

J = Load Transfer Coefficient

?PSI = Change in Serviceability Index

p_o = Initial Serviceability Index

p_t = Terminal Serviceability Index

D = Pavement Thickness

f'_c = Compressive Strength

The standard deviate is based on reliability. The reliability used for this study is 80% and is obtained from the design chart provided in Appendix D. Using a reliability of 80% the standard deviate is found in the design chart also provided in Appendix D.

The elastic modulus of concrete is based on the compressive strength of the pervious concrete (f'_c). The equation for finding the elastic modulus is given by:

$$E_c = 57000\sqrt{f'_c}$$

Source: Huang (2003), *Pavement Analysis and Design*, p. 580.

The modulus of subgrade reaction is dependent on the type of soil beneath the pervious concrete. Research indicates that typical soils range from 50-400 pci and these are the values utilized in this study.

The modulus of rupture of conventional concrete falls within the range of $8vf'_c$ to $10vf'_c$ (Huang, 2003). In 1976, Malhotra calculated the modulus of rupture of pervious concrete to be 10.8 to 31.0% of the compressive strength. For the purposes of this research the following equation is used which is 22% of the compressive strength of the pervious concrete.

$$S_c = 9\sqrt{f_c'}$$

The drainage coefficient is dependent on the expected exposure of the concrete to saturation levels and the amount of time required to remove water from the system. This value is obtained from a design table provided in Appendix D.

The compressive strength is the maximum value obtained from testing from an acceptable cylinder.

The load transfer coefficient is dependent on the traffic volume and varies as the ESAL changes. These values are provided in a table in Appendix D.

The initial serviceability index represents the condition of the pavement when newly constructed. The terminal serviceability index is the lowest index reached before any rehabilitation of the pavement surface. The change in serviceability indexes is the subtraction of the terminal index from the initial index.

All variables used in calculating pavement thicknesses are provided in Table 3.7.1.

Table 3.7.1 Parameters and Values

Fixed		Variable	
Z	-0.841	ADT	500-3500
S_o	0.3	T	.05-.20
p_o	4.5	k	50-400
p_t	2	J	2.8-3.1
?PSI	2.5		
S_c	371		
C_d	1.1		
E_c	2350170		
f'_c	1700		
GY	29.78		
T_f	0.24		
D	1		
L	1		

4.0 FINDINGS

4.1 Introduction

This chapter will extensively discuss the results of the experiments described in the previous chapter. Comparisons will be provided of relevant relationships between water, aggregate, and cement to show the influence each has on one another. Tables indicating minimum pavement thickness levels will also be given.

4.2 Specific Gravity and Unit Weight of the Aggregate

Two experiments were conducted in order to determine the specific gravity and unit weight of the aggregate used in this research. Both tests yielded an identical result. The specific gravity of the aggregate was calculated to be 2.36 and its corresponding unit weight was determined to be 147.53 lb/ft^3. The results from both tests are provided in Table 4.2.1.

Table 4.2.1. Specific Gravity Experiments - Aggregate

Item	Test 1	Test 2
Mass of container + water (W1)(lbs)	15.89	15.78
Mass of container + water + aggregate (W2)(lbs)	20.6	20.49
Mass of aggregate (W3)(lbs)	8.16	8.16
Mass of equal volume of water as the aggregate (W4=(W1+W3)-W2)(lbs)	3.45	3.45
Specific Gravity (G=W3/W4)	2.36	2.36
Unit Weight (lb/ft^3)	147.53	147.53

4.3 Cylinders used for Testing

Photographs taken of the side and base of each cylinder are provided in Appendix C. The visible physical characteristics of the cylinders can provide preliminary information it prior to subjecting the cylinders to any tests. For example, too much water in a mixture would cause the cement to sink to the bottom of the cylinder. The result would be clogging of the void spaces in the base of the concrete and prevent permeability of water. Visually the bottom portion of the cylinder would be solid, there would be no voids, and it might appear as if it was conventional concrete. Higher compressive strengths and lower permeability rates can be expected from these cylinders due to the lack of void spaces. With the movement of the cement to the bottom of the cylinder, the top portion might be weaker than the bottom. Failure would begin at the top surface and work its way down the cylinder. The result might not be an abrupt failure but a long process in which the loading may actually increase after initially crushing the top and continue until the entire cylinder fails.

In examining the photographs of all the mixtures, predictions can be made about their expected behaviors. All the cylinders in mixture 1 have bases that are completely clogged. Expectations are that the cylinders will have little or no permeability capabilities and provide higher compressive strengths when compared to the other cylinders.

Mixture 2 produced cylinders that still have clogging at their bottoms but not to the same degree as in mixture 1. Since the A/C ratio is identical, the decrease in clogging is strictly due to the W/C ratio. Mixture 2 has less water therefore it did not wash all of the cement to the bottom. Permeability rates can be expected to increase from those in mixture 1 but compressive strength will be less than mixture 1 due to its departure from conventional concrete characteristics.

Photographs of the bases of mixture 3 cylinders appear to be slightly better than mixture 2. Clogging is still apparent and expectations are that the permeability rates may be comparable to mixture 2. Nothing suggests that the strength of the cylinders in mixture 3 will be lower or higher than the strength of mixture 2.

Mixture 4 gives the appearance of having permeability rates comparable to mixture 2. Clogging is prevalent on the bases of the cylinders but interestingly there does not appear to be as much clogging on the sides of the cylinders as in mixture 2. This leads to the assumption that the voids are dispersed more evenly throughout mixture 4 thereby producing a better permeability rate. An even dispersement of voids lends to the assumption that the aggregate is better aligned and able to withstand higher compressive loads than in mixture 2.

The remaining mixtures have an increase in the A/C ratios. These cylinders appear “dry” as if not enough cement was present to properly coat the aggregate and produce a solid bond. Some of the cylinders show a small amount of clogging on the base but the remainder of the cylinder is free from any type of clogging. It is difficult to see the cement paste surrounding the aggregate. Expectations are that the remaining four mixtures will provide extremely high permeability rates but very low compressive strengths due to lack of correct bonding between aggregate.

4.4 Permeability, Specific Gravity, and Compressive Strength of Pervious Concrete

4.4.1 Permeability

Permeability rates are consistent with expectations from visual observations of the cylinders. The results of the permeability tests are provided in Table 4.4.1. Permeability rates in the first mixtures are considerably less than the later mixtures. In fact rates from mixtures 1 and 2 are limited by the amount of cement that had collected in the base of the cylinder. Permeability rates are also relatively consistent with compaction and density. Higher compaction energies increase the density thereby reducing the porosity of the concrete. The reduction in porosity leads directly to a reduction in the permeability rate. Mixtures 5, 6, 7, and 8 indicate a reduction in permeability rates ranging from 50-68% when modified Proctor compaction is utilized.

Permeability rates obtained in this experiment are also consistent with what prior researchers have found. Although a wide range of permeability rates were seen from this experiment, they are not typically the limiting factor. Water flow through pervious concrete is usually restricted by the permeability rates of the soil beneath the concrete. This being said, the permeability rates obtained from mixture 1 would not be acceptable because the water flow was limited to almost nothing. Higher permeability rates in pervious concrete is advantageous as it allows for clogging of the void spaces without being detrimental to the flow of water through the concrete.

Table 4.4.1 Permeability Experiments

Mix	No.	Water Cement Ratio (by weight)	Aggregate Cement Ratio (by Volume)	Compaction	Weight of Cylinder and Concrete (Wet)	Weight of Concrete (Dry)	Permeability (in/hr)
1	1111	0.52	4.00	Standard	7.18	6.78	
	1112			Standard	7.16	6.83	0
	1121			Modified	7.32	6.92	
	1122			Modified	7.40	7.07	138
2	2111	0.39	4.00	Standard	7.20	6.82	
	2112			Standard	7.04	6.69	655
	2121			Modified	7.10	6.70	
	2122			Modified	6.98	6.65	1085
3	3211	0.44	5.00	Standard	6.88	6.50	
	3212			Standard	6.90	6.57	1085
	3221			Modified	6.90	6.48	
	3222			Modified	6.92	6.59	1034
4	4211	0.35	4.00	Standard	6.66	6.30	
	4212			Standard	6.96	6.63	1241
	4221			Modified	7.08	6.72	
	4222	---Void---	---Error---	Modified	---Error---	---Void---	---Error---
5	5311	0.33	6.00	Standard	6.62	6.24	
	5312			Standard	6.64	6.31	2068
	5321			Modified	6.68	6.28	
	5322			Modified	6.76	6.45	1310
6	6311	0.38	6.00	Standard	6.60	6.20	
	6312			Standard	6.58	6.25	2137
	6321			Modified	6.86	6.48	
	6322			Modified	6.82	6.49	1447
7	7411	0.32	7.00	Standard	6.46	6.04	
	7412			Standard	6.40	6.09	2688
	7421			Modified	6.76	6.36	
	7422			Modified	6.68	6.37	1378
8	8411	0.39	7.00	Standard	6.56	6.14	
	8412			Standard	6.52	6.21	2412
	8421			Modified	6.96	6.54	
	8422			Modified	6.88	6.55	1206

4.4.2 Specific Gravity and Unit Weight

Specific gravity tests were performed on all cylinders in order to obtain unit weight and porosity. The results of these experiments are given in Table 4.4.2. Porosity ranges from 3-29% which is consistent with other researchers' findings. The lower porosity percentages are limited to mixtures 1 and 2. Once again the high amount of cement is the contributing factor in this lower porosity. The cement, when mixed with water, work to clog the void spaces in the pervious concrete. The result is concrete that more closely resembles conventional concrete than pervious concrete. Researchers have also concluded that the unit weight of pervious concrete is usually 70-75% that of conventional concrete. The results from testing these cylinders are no exception.

Table 4.4.2 Specific Gravity Experiments - Concrete

Item	Cylinder							
	1111	1112	1121	1122	2111	2112	2121	2122
Mass of container + water (W1)	19.14	19.18	19.03	18.98	19.16	18.88	18.98	19.04
Mass of container + water + concrete (W2)	22.60	22.60	22.50	22.52	22.72	22.25	22.72	22.28
Mass of concrete (W3)	6.78	6.83	6.92	7.07	6.82	6.69	6.70	6.65
Mass of equal volume of water as the concrete (W4=(W1+W3)-W2)	3.32	3.41	3.45	3.53	3.26	3.32	2.96	3.41
Specific Gravity (G=W3/W4)	2.04	2.00	2.01	2.00	2.09	2.01	2.26	1.95
Unit Weight of Concrete (lb/ft^3)	116.54	117.40	118.95	121.52	117.23	114.99	115.16	114.31
Volume of Concrete (ft^3)	0.053	0.055	0.055	0.057	0.052	0.053	0.047	0.055
Volume of Voids (ft^3)	0.005	0.004	0.003	0.002	0.006	0.005	0.011	0.004
Void Ratio	0.09	0.06	0.05	0.03	0.11	0.09	0.23	0.06
Porosity	0.09	0.06	0.05	0.03	0.10	0.08	0.18	0.06

Item	Cylinder							
	3211	3212	3221	3222	4211	4212	4221	4222
Mass of container + water (W1)	19.22	18.96	18.82	18.90	18.90	18.84	19.12	Void
Mass of container + water + concrete (W2)	22.60	22.40	22.22	22.34	22.32	22.44	22.56	Void
Mass of concrete (W3)	6.50	6.57	6.48	6.59	6.30	6.63	6.72	Void
Mass of equal volume of water as the concrete (W4=(W1+W3)-W2)	3.12	3.13	3.08	3.15	2.88	3.03	3.28	Void
Specific Gravity (G=W3/W4)	2.08	2.10	2.10	2.09	2.19	2.19	2.05	Void
Unit Weight of Concrete (lb/ft^3)	111.73	112.93	111.38	113.27	108.29	113.96	115.51	Void
Volume of Concrete (ft^3)	0.050	0.050	0.049	0.050	0.046	0.049	0.053	Void
Volume of Voids (ft^3)	0.008	0.008	0.009	0.008	0.012	0.010	0.006	Void
Void Ratio	0.16	0.16	0.18	0.15	0.26	0.20	0.11	Void
Porosity	0.14	0.14	0.15	0.13	0.21	0.17	0.10	Void

Table 4.4.2 Specific Gravity Experiments - Concrete

Item	Cylinder							
	5311	5312	5321	5322	6311	6312	6321	6322
Mass of container + water (W1)	18.88	19.04	18.90	19.10	18.70	18.92	18.74	18.96
Mass of container + water + concrete (W2)	22.30	22.44	22.48	22.44	22.34	22.14	22.20	22.36
Mass of concrete (W3)	6.24	6.31	6.28	6.45	6.20	6.25	6.48	6.49
Mass of equal volume of water as the concrete (W4=(W1+W3)-W2)	2.82	2.91	2.70	3.11	2.56	3.03	3.02	3.09
Specific Gravity (G=W3/W4)	2.21	2.17	2.33	2.07	2.42	2.06	2.15	2.10
Unit Weight of Concrete (lb/ft^3)	107.26	108.46	107.95	110.87	106.57	107.43	111.38	111.55
Volume of Concrete (ft^3)	0.045	0.047	0.043	0.050	0.041	0.049	0.048	0.050
Volume of Voids (ft^3)	0.013	0.012	0.015	0.008	0.017	0.010	0.010	0.009
Void Ratio	0.29	0.25	0.34	0.17	0.42	0.20	0.20	0.17
Porosity	0.22	0.20	0.26	0.14	0.29	0.17	0.17	0.15

Item	Cylinder							
	7411	7412	7421	7422	8411	8412	8421	8422
Mass of container + water (W1)	18.88	18.90	18.94	19.02	18.76	19.12	18.92	19.00
Mass of container + water + concrete (W2)	22.26	22.26	22.50	22.38	22.30	22.20	22.48	22.34
Mass of concrete (W3)	6.04	6.09	6.36	6.37	6.14	6.21	6.54	6.55
Mass of equal volume of water as the concrete (W4=(W1+W3)-W2)	2.66	2.73	2.80	3.01	2.60	3.13	2.98	3.21
Specific Gravity (G=W3/W4)	2.27	2.23	2.27	2.12	2.36	1.98	2.19	2.04
Unit Weight of Concrete (lb/ft^3)	103.82	104.68	109.32	109.49	105.54	106.74	112.41	112.59
Volume of Concrete (ft^3)	0.043	0.044	0.045	0.048	0.042	0.050	0.048	0.051
Volume of Voids (ft^3)	0.016	0.014	0.013	0.010	0.017	0.008	0.010	0.007
Void Ratio	0.36	0.33	0.30	0.21	0.40	0.16	0.22	0.13
Porosity	0.27	0.25	0.23	0.17	0.28	0.14	0.18	0.12

4.4.3 Compression Testing

All of the mixing, ratios, calculations, and testing culminate into the final experiment, compression testing. Graphs indicating loading versus displacement over time for each cylinder are given in Appendix C. Maximum compressive strengths attained for each of the cylinders are provided in Table 4.4.3. Again results are consistent with visual observations. Mixtures 5, 6, 7, and 8 provide the least compressive strengths of all the mixtures. This is due to the lack of cement to bond the aggregate together. Mixtures 1, 2, 3, and 4 yielded the highest compressive strengths. However the strengths yielded by mixtures 1 and 2 are deceptively high. Cement that settled at the bottom of the cylinders in these mixtures is what gives the concrete its strength. Under real applications the water would have sent the cement completely through the aggregate and into the subbase, leaving the aggregate with little cement for bonding. Although a wide range of compressive strengths were obtained, none of the mixtures provide strength equal to that of conventional concrete.

In comparing compressive strength with the W/C ratio and different A/C ratios, it is shown that an increase in the A/C ratio results in a decrease in its strength. Although the W/C ratio influences the strength of pervious concrete, it alone does not dictate the potential strength of the concrete. Figures 4.4.1and 4.4.2 show the relationship of strength versus W/C ratio and A/C ratio.

Table 4.4.3 Maximum Compressive Strength

Mix	No.	Water Cement Ratio (by weight)	Aggregate Cement Ratio (by Volume)	Compaction Energy (kN-m/m^3)	Compressive Strength (psi)
1	1111	0.52	4.00	341	2188*
	1112			341	1537
	1121			1544	1750
	1122			1544	1750
2	2111	0.39	4.00	341	1516
	2112			341	1433
	2121			1544	1242
	2122			1544	1534
3	3211	0.44	5.00	341	1417
	3212			341	1251
	3221			1544	1487
	3222			1544	1484
4	4211	0.35	4.00	341	1686
	4212			341	1494
	4221			1544	1716
	4222	---Void---	---Error---	1544	---Void---
5	5311	0.33	6.00	341	830
	5312			341	1050
	5321			1544	843
	5322			1544	970
6	6311	0.38	6.00	341	811
	6312			341	836
	6321			1544	1012
	6322			1544	1067
7	7411	0.32	7.00	341	717
	7412			341	679
	7421			1544	830
	7422			1544	743
8	8411	0.39	7.00	341	715
	8412			341	579
	8421			1544	1000
	8422			1544	866

*Compaction energy exceeded 341 kN-m/m^3 due to error in testing procedures.

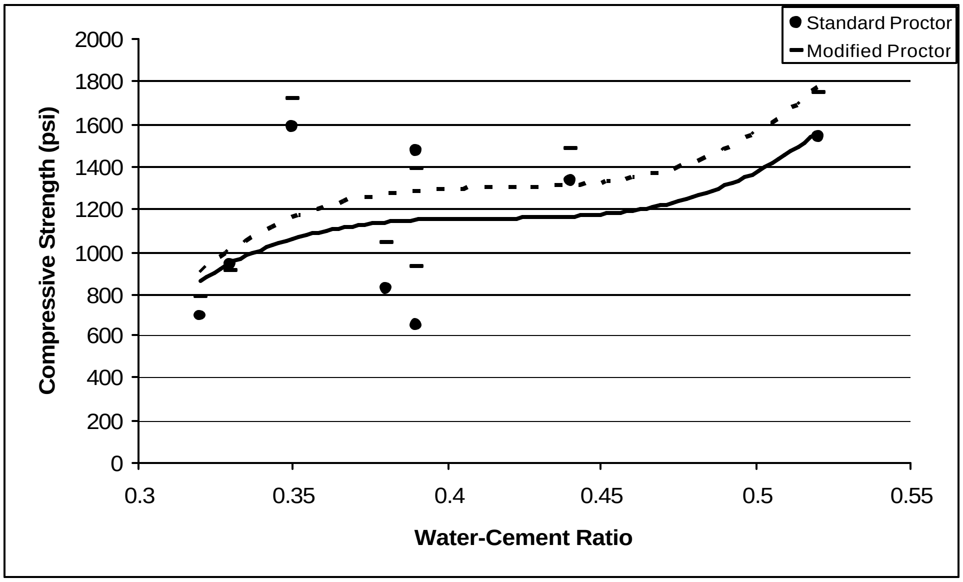


Figure 4.4.1 Strength vs W/C Ratio

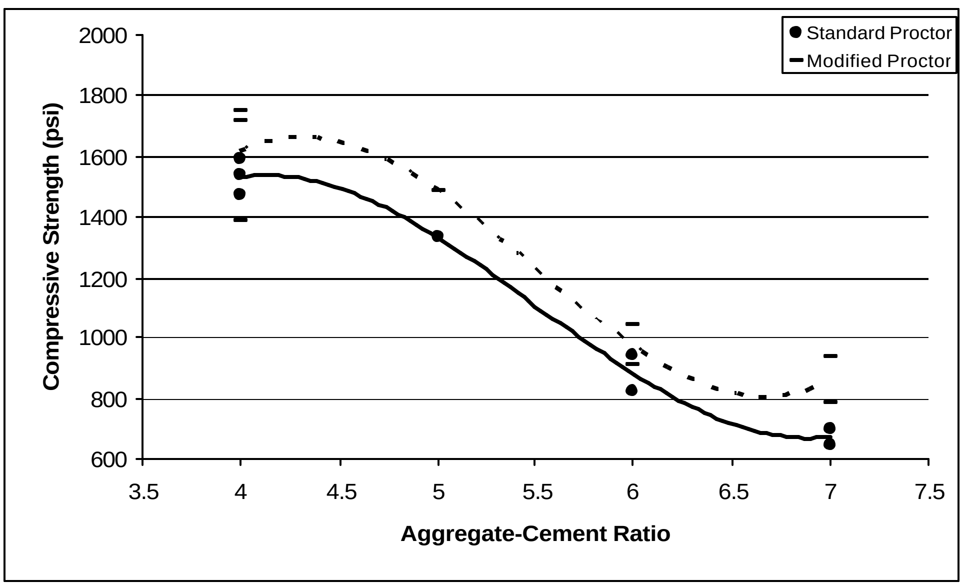


Figure 4.4.2 Strength vs A/C Ratio

The strength of pervious concrete is strongly dependent on the A/C ratio and compaction energy. The A/C ratio is interpreted into porosity. More cement decreases porosity and increases unit weight. Higher compaction energies result in higher unit weights which yield higher strengths. The experiments conducted on these cylinders are consistent with these findings. Figures 4.4.3 and 4.4.4 show relationships between unit weight and strength and unit weight and porosity.

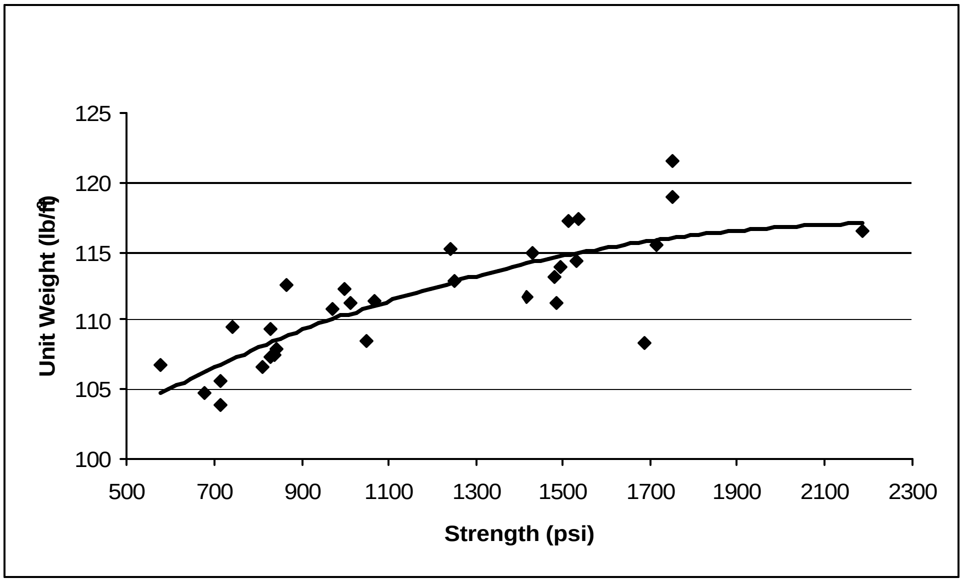


Figure 4.4.3 Unit Weight vs Strength

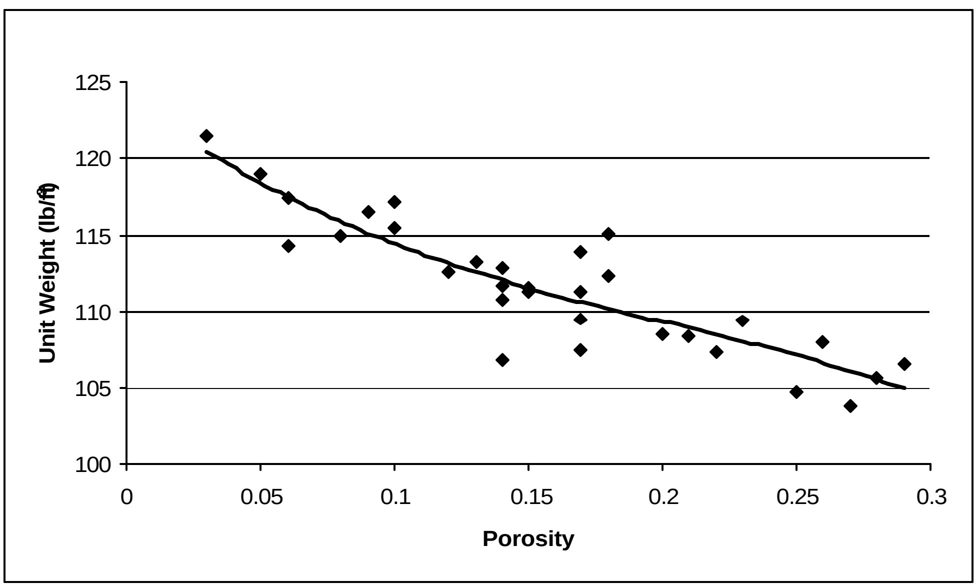


Figure 4.4.4 Unit Weight vs Porosity

Permeability is affected by the A/C ratio. As the amount of cement in a mixture decreases, which indicates an increase in the A/C ratio, the permeability of the pervious concrete increases. This relationship is shown in Figure 4.4.5.

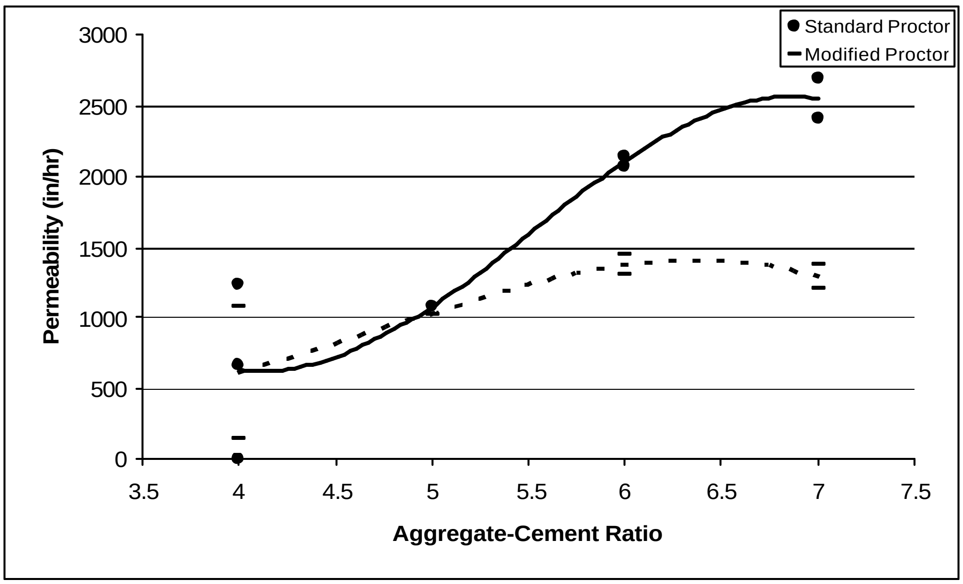


Figure 4.4.5 Permeability vs A/C Ratio

Permeability can also be related to compressive strength. The compressive strength of pervious concrete increases with the presence of more cement in the mixture, which is a decrease in the A/C ratio. More cement in the mixture would fill void spaces once occupied by air, thereby reducing the permeability of the concrete. This is represented by Figure 4.5.6.

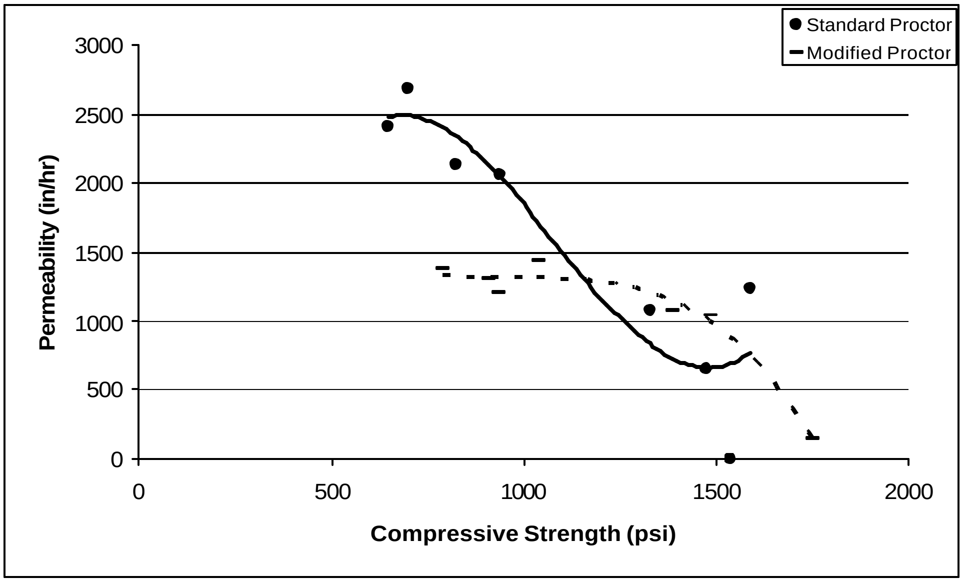


Figure 4.4.6 Permeability vs Compressive Strength

4.5 Site Investigation of Existing Systems

4.5.1 Parking Area 1 – Florida Concrete and Products Association

This area consists of 13 total parking stalls. The driveway portion and the 7 parking stalls located on the south side of the parking lot are constructed of asphalt. This asphalt area drains onto the remaining 6 parking stalls on the north side of the parking lot. These 6 stalls consist of pervious concrete. A drain exists in the northeast corner of the parking lot in one of the pervious concrete stalls. Estimated yearly traffic for this pervious concrete area is 1,500 vehicles. Calculations are provided in Appendix A. Calculations are based on the assumption that these 6 parking stalls are utilized every day during the week. This parking area is not subjected to heavy truck loads and only sees light automobile traffic. This would subject the pervious concrete to loads approximating 3,000 to 6,000 pounds.

The pervious concrete area, constructed in 1999, shows minimal damage. Minor cracks are located throughout the area. Of particular interest is the amount of algae forming on the pervious concrete. Along the north edge of the parking spaces and also along the eastern edge, a significant amount of algae have settled onto the surface. Although structurally insignificant, this can have a detrimental impact on the filtration characteristics. Figure 4.5.1 provides a detailed sketch of parking area 1.

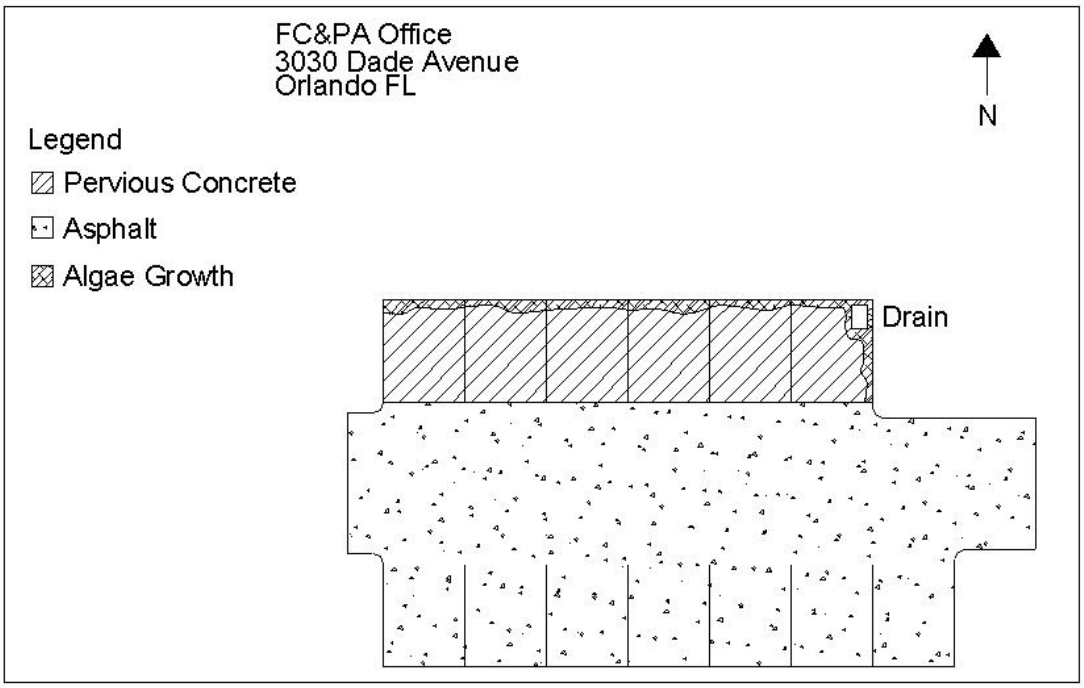


Figure 4.5.1. Parking Area 1 – FC&PA Office

4.5.2 Parking Area 2 – Sun Ray Store Away

This place of business utilizes pervious concrete not in its parking lot but in its roadway system just inside the gates. This is a storage facility subjected to a variety of loads. Automobiles as well as moving trucks, vans, and semi-tractor trailers utilize this facility thereby subjecting the pervious concrete to a high amount of compression loads throughout the day. These types of trucks can weigh anywhere from 14,000 pounds for straight trucks to 80,000 pounds for semi-tractor trailers. In addition to the 823 storage units available for rental, this facility also has 62 parking spaces utilized for large vehicle storage. On property are items such as boats on trailers, which can weigh upwards of 53,000 pounds, and recreational vehicles, which can reach weights of 45,000 pounds. It is estimated that this facility sees approximately 66,800 vehicles on a yearly basis. See Appendix A for calculations. Calculations are made utilizing the Trip Generation Manual from 1991.

Damage to this pervious concrete system is limited to two areas, one is the area just inside the gate and the other is the area in front of the garbage dumpster. Considering that all traffic coming into the facility passes over the area inside the gate, it is not surprising that a significant number of cracks are present. It appears, however, that the garbage truck subjects the pervious concrete to extreme loads when emptying the dumpster thereby causing cracking in the area in front of the dumpster. Figure 4.5.2 is a detailed drawing of this area.

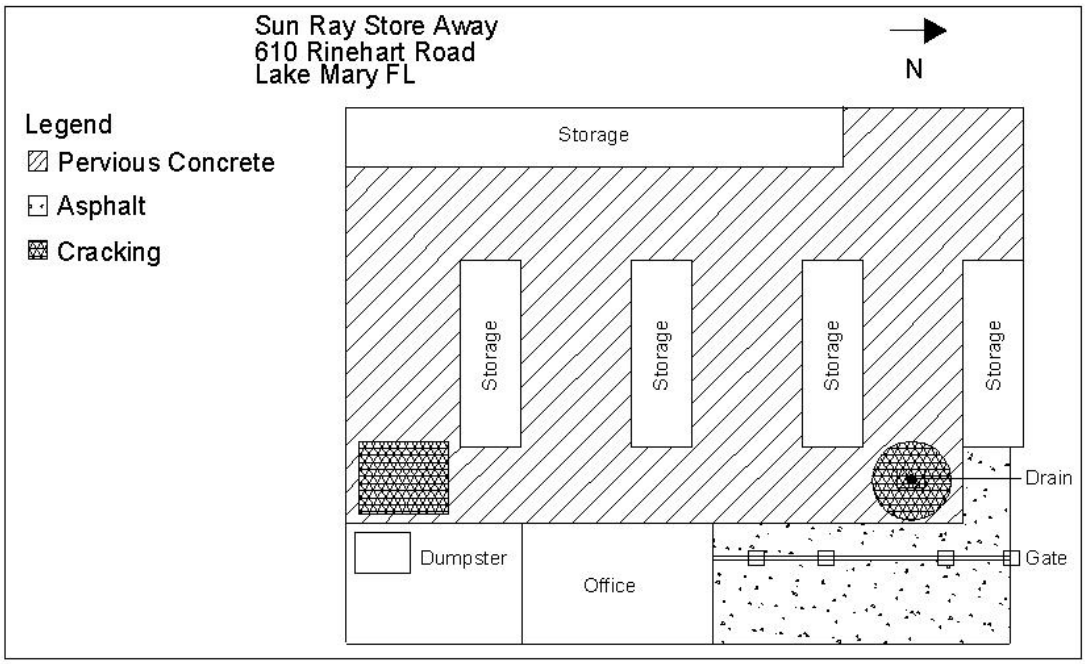


Figure 4.5.2. Parking Area 2 – Sun Ray Store Away

4.5.3 Parking Area 3 – Strang Communications

This parking lot for a 200 employee office building is subjected to the highest volume of traffic of all the pervious concrete areas studied for the purposes of this research. There are 71 parking stalls in three rows in this lot that are made using pervious concrete. That is approximately 50% of the total parking lot. The remaining stalls consist of asphalt. The pervious concrete is limited to the stalls themselves and the areas directly behind them. The main entrances into the parking lot are constructed of asphalt. The pervious concrete area is subjected to automobiles volumes approximating 213,200 vehicles per year. These loads are approximately 3,000 to 6,000 pounds. Calculations are provided in Appendix A. Calculations are made utilizing the Trip Generation Manual from 1991.

Constructed in 1991, this lot has minimal damage throughout. There is one area where a significant amount of raveling has taken place. Raveling is the deterioration of the concrete due to repeated loads over time on an area. The 9 spaces located in the northwest area of the pervious concrete are raveling at the entrance to each stall. Since these spaces are closest to the building, they would be subjected to the most traffic. There is also a small amount of raveling at the entrance to the parking row on the west. Again this is due to repeated traffic. Algae have also made a significant presence in this parking lot. Figure 4.5.3 shows the location of the raveling and algae in this parking area.

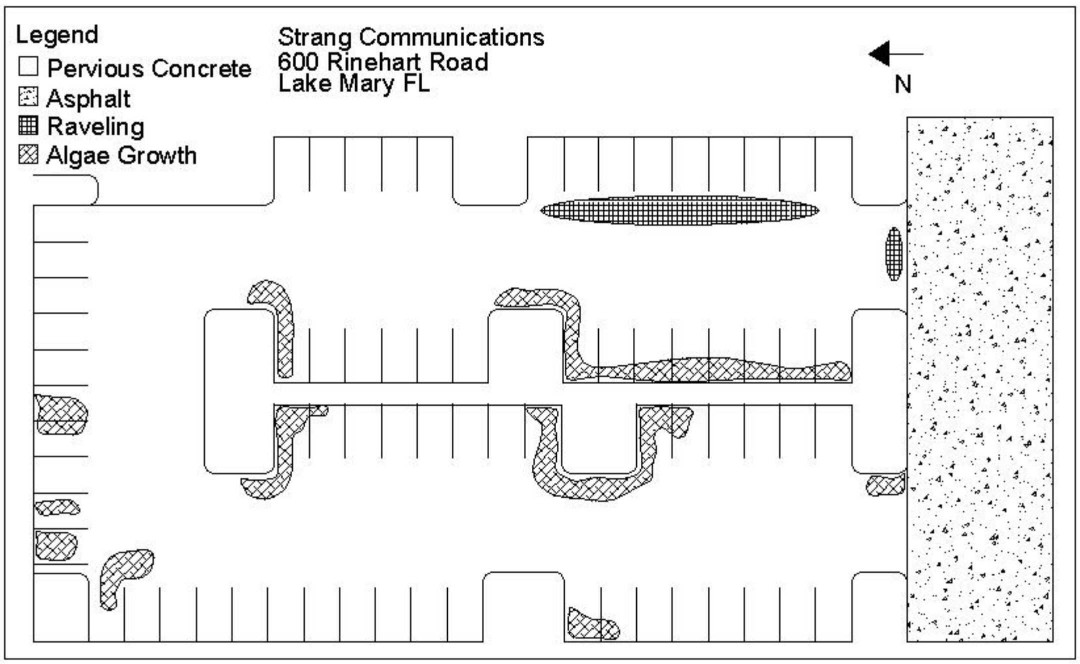


Figure 4.5.3. Parking Area 3 – Strang Communications

4.5.4 Parking Area 4 – Murphy Veterinary Clinic

This is a 13 space parking lot constructed in 1987. It is subjected to low traffic volumes and loads, approximately 11,200 vehicles per year. The loads on this pervious concrete would be approximately 3,000 to 6,000 pounds per vehicle. Calculations are provided in Appendix A. This facility employs 4 persons and schedules patients in 15 minute increments. Calculations are based on the assumption that this business sees 4 patients each hour for the 8 hour day.

There are two entrance/exit points located at the east and west sides of the lot. The pervious concrete driveway on the west side stops just short of the garbage dumpster. The driveway connecting the pervious concrete to the roadway is constructed of asphalt. This is so not to subject the pervious concrete to the heavy loads of the garbage truck. The pervious concrete driveway on the east side stops short of the main roadway by approximately 15 feet. This 15 foot section is made of conventional concrete. The builders, recognizing this area would be subjected to a high degree of stress from vehicles turning into the driveway, placed a stronger material to withstand those stresses.

This parking area is in remarkable condition for having been constructed 17 years ago. There is no damage in any of the expected areas, the entrance points to the lot and to the individual stalls. Figure 4.5.4 provides graphical representation of this parking area.

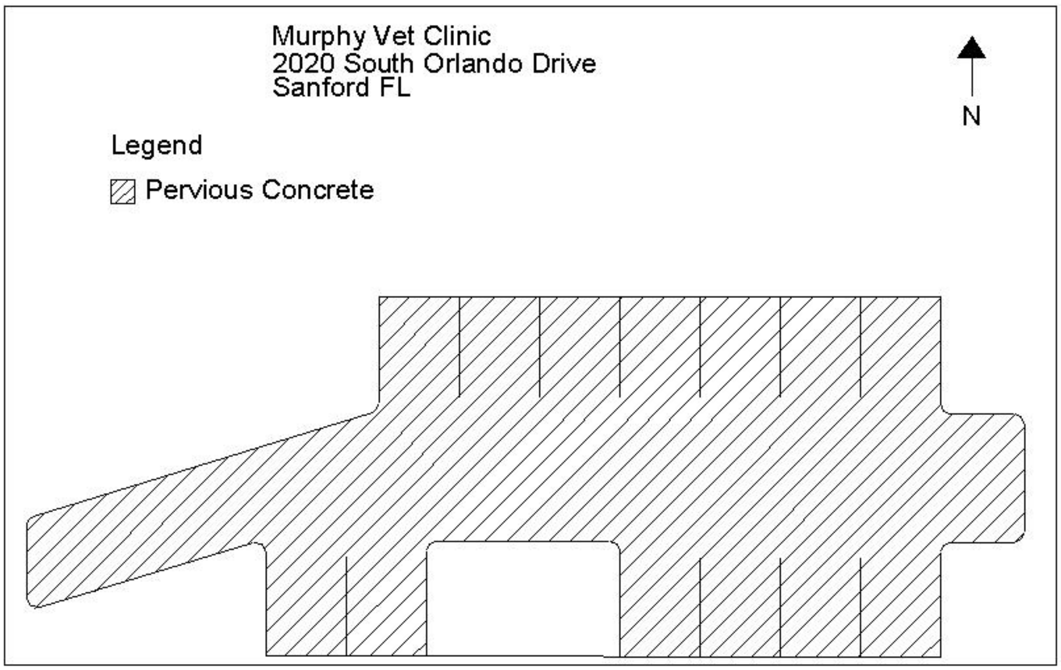


Figure 4.5.4. Parking Area 4 – Murphy Veterinary Clinic

4.5.5 Parking Area 5 – Dental Office

Built in 1991, this 17 space parking lot is part of a small medical plaza. It is subjected to a volume of vehicles during the year equal to approximately 9,600 vehicles. The pervious concrete in this parking lot would be subjected to loads approximating 3,500 pounds per automobile. However the garbage truck would subject the pervious concrete to a significantly higher loading of approximately 31,000 – 51,000 pounds depending on the weight of the load. Calculations are provided in Appendix A. This office employs 5 persons and schedules appointments in 15 minute increments. Calculations are based on the assumption that 4 patients are seen every hour for the entire 8 hour day.

This parking area has significant damage throughout the lot. Unlike the other parking areas in this study, this lot has a driveway constructed of pervious concrete. Not only is this area subjected to the loadings of every vehicle that enters the facility, the weekly garbage truck utilizes the driveway to gain access to the dumpster located just north of the entrance. The result is a large amount of raveling and crushing throughout the entire entrance. There is also a considerable amount of raveling in front of the 4 parking stalls just inside the entrance. These would be the spaces utilized the most when entering the lot. Algae growth in this lot is minimal. Figure 4.5.5 shows the damage in this particular lot.

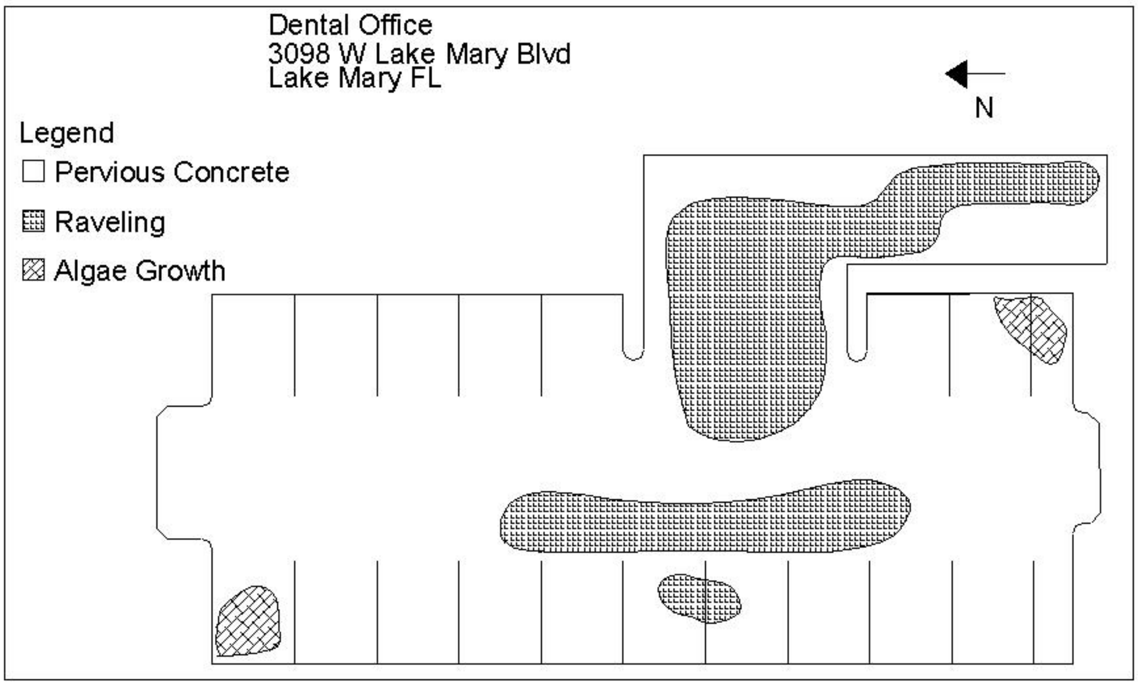


Figure 4.5.5. Parking Area 5 – Dental Office

4.6 Design Vehicles

This study will determine the acceptable level of vehicular loads on pervious concrete pavements based on the compressive strength results obtained from experiments. AASHTO classifies vehicles into four classes; passenger cars, buses, trucks, and recreational vehicles. Within those four classes fifteen separate types of vehicles are defined. Table 4.6.1 lists the fifteen types of vehicles defined by AASHTO. AASHTO breaks down these categories due to changes in dimensions.

Table 4.6.1 Design Vehicles

Design Vehicle Type	Symbol
Passenger Car	P
Single-Unit Truck	SU
Buses	
Intercity Bus	BUS-12
City Transit Bus	CITY-BUS
Conventional School Bus (65 pass.)	S-BUS 11
Large School Bus (84 pass.)	S-BUS 12
Articulated Bus	A-BUS
Trucks	
Intermediate Semitrailer	WB-12
Intermediate Semitrailer	WB-15
Interstate Semitrailer	WB-19
Interstate Semitrailer	WB-20
Double-Bottom-Semitrailer/Trailer	WB-20D
Triple-Semitrailer/Trailer	WB-30T
Turnpike Double-Semitrailer/Trailers	WB-33D
Recreational Vehicles	
Motor Home	MH
Car and Camper Trailer	P/T
Car and Boat Trailer	P/B
Motor Home and Boat Trailer	MH/B
Farm Tractor	TR

Source: A Policy on Geometric Design of Highways and Streets, 2004, p.17.

Each of the vehicles provides varying turning radii which is crucial in highway design. For the purpose of this research, however, dimensions are not as significant as the vehicle weight. Although the vehicles within the same class have varying dimensions, there weights generally fall within a common range. Vehicle manufacturers divide vehicles into eight separate weight classes. These weight classes are provided in Table 4.6.2. Also included in this table is the maximum weight any one axle or axle group would be subjected to at any time with the exception to Class 8 vehicles. Class 8 represents a wide variety of vehicles that have different weight distributions. Table 4.6.3 represents some of the vehicles from Class 8 and their corresponding maximum axle weight.

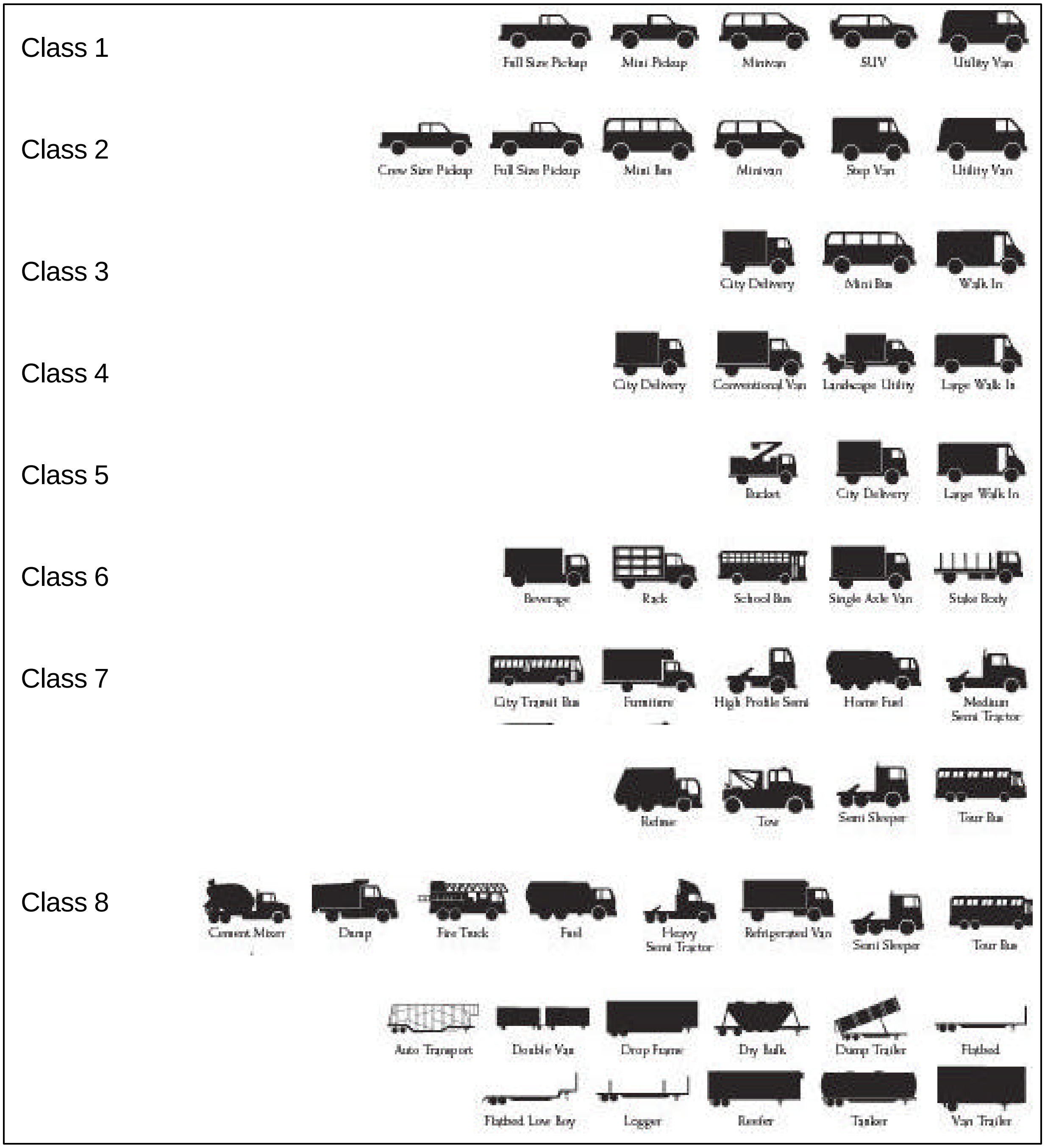
Table 4.6.2 Weight Classifications

Weight Classifications	GVWR	Weight Pounds (lbs)	Maximum Weight/Axle	Maximum Weight/Wheel
Light	Class 1	6,000 or less	3,600	1,800
	Class 2	6,001 - 10,000	6,000	3,000
Medium	Class 3	10,001 - 14,000	11,200	5,600
	Class 4	14,001 - 16,000	12,800	6,400
	Class 5	16,001 - 19,500	15,600	7,800
	Class 6	19,501 - 26,000	20,800	10,400
Medium Heavy Duty	Class 7	26,001 - 33,000	26,400	13,200
Heavy Duty	Class 8	33,001 or over		

Table 4.6.3 Class 8 Vehicles – Weight Classification

Class 8 Vehicles	Axles	Weight Pounds (lbs)	Maximum Weight/Axle	Maximum Weight/Wheel
Tractor Trailer	5	80,000 - 90,000	32,000 - 39,600	16,000 - 19,800
	6	80,000 - 100,000	38,400 - 48,000	19,200 - 24,000
Turnpike Double	9	105,500 - 147,000	32,000 - 33,500	16,000 - 16,750
Tour Bus	3	50,000	40,000	20,000
Single Unit Truck	2 or 3	40,000 - 65,000	32,000 - 52,000	16,000 - 26,000
	4	62,000 - 70,000	24,800 - 28,000	12,400 - 14,000
Motor Home		45,000	27,000	13,500

Figure 4.6.1 gives a graphical representation of the types of vehicles that are attributed to each of the eight classifications.



Source: www.ctea.on.ca

Figure 4.6.1 Design Vehicles

Figures 4.6.2 and 4.6.3 compare the maximum weight of one wheel or wheel group of each of the vehicle classes with compressive strength attained when testing the pervious concrete cylinders. The graphs indicate whether the pervious concrete tested would be able to support a static load of the indicated vehicles. The graphs are divided into acceptable and unacceptable pervious concrete mixtures. Mixtures 5 through 8 provided such low compressive strength they would not be considered acceptable for any application and are therefore the comparisons are given in a separate graph.

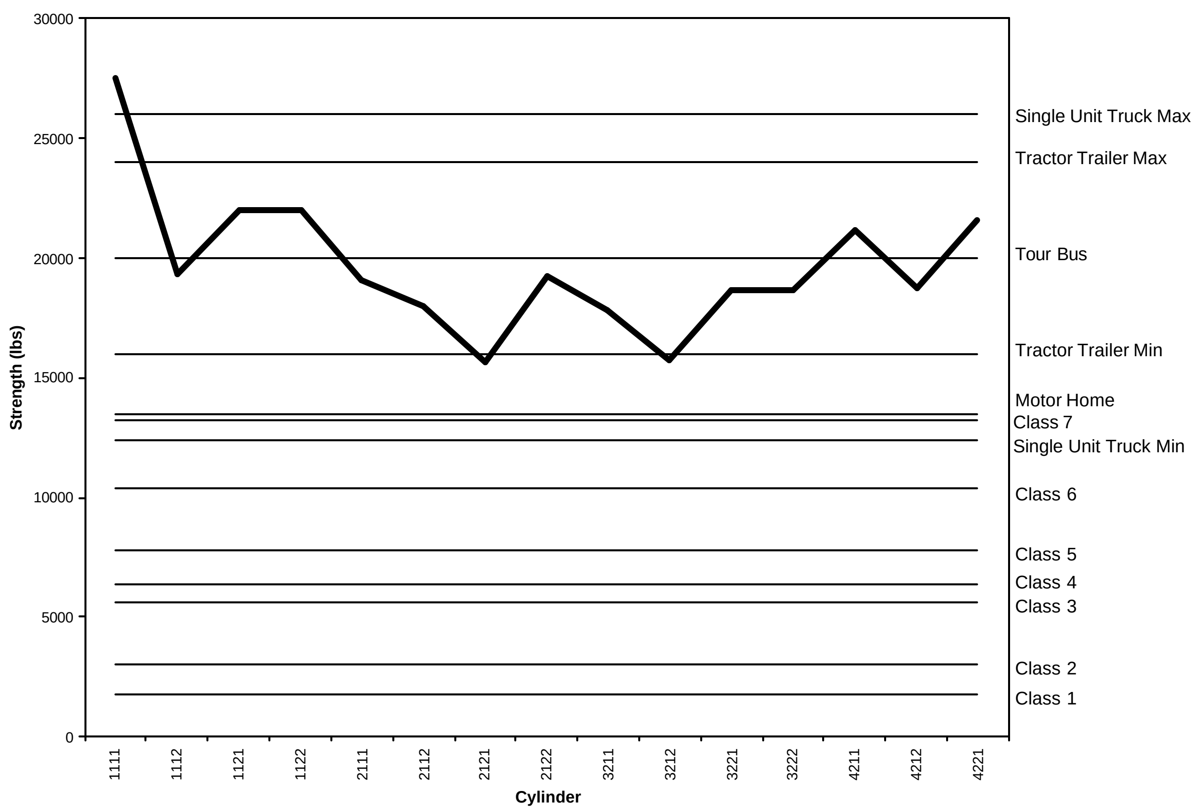


Figure 4.6.2 Vehicle Class Weights vs Cylinder Compressive Strengths-Acceptable Mixtures

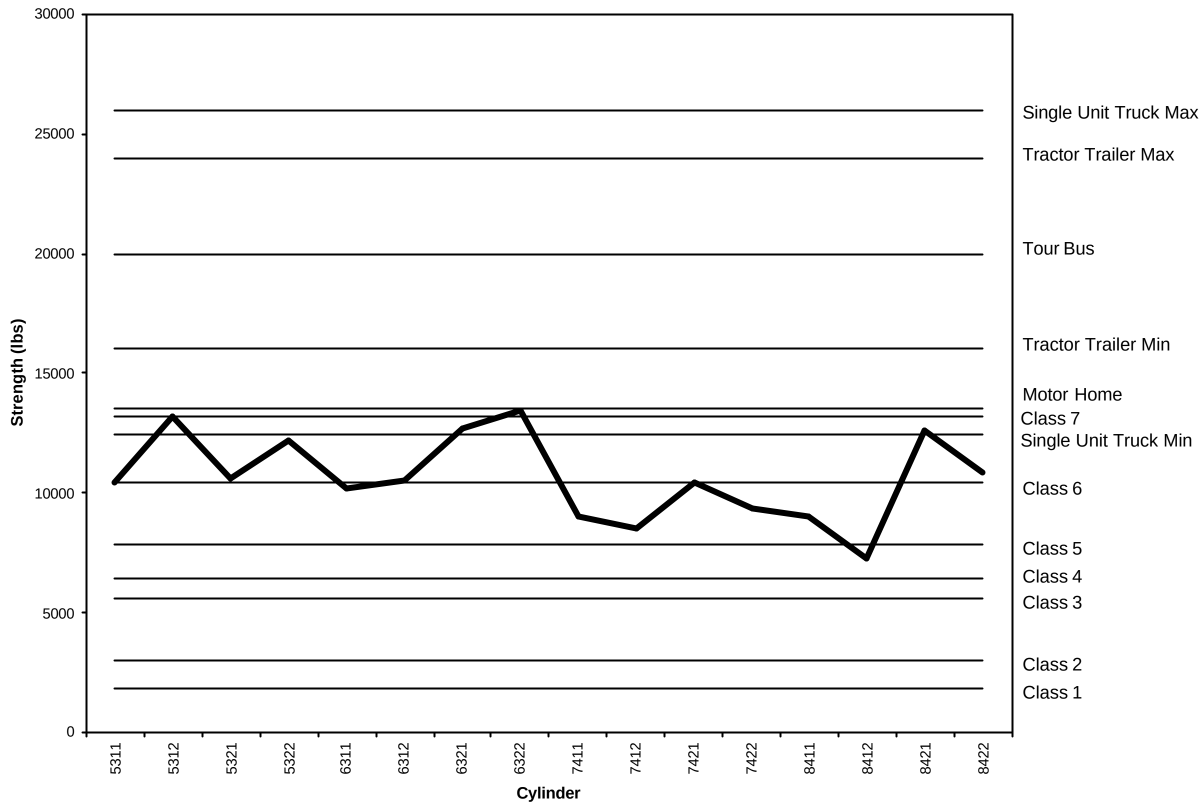


Figure 4.6.3 Vehicle Class Weights vs Cylinder Compressive Strengths-Unacceptable Mixtures

4.7 Pavement Thickness Design

Utilizing the parameters discussed in the previous section, minimum pavement thicknesses for varying soil types, vehicle loadings, and percentage of trucks were calculated and are provided in Table 4.7.1, Table 4.7.2, Table 4.7.3, and Table 4.7.4.

Table 4.7.1 Minimum Pavement Thickness for 5% Trucks

k (pci)	ADT 500	750	1000	1250	1500	1750	2000	2250	2500	3000	3500
50	4.9	5.3	5.6	5.8	6.0	6.1	6.3	6.4	6.8	7.0	7.2
75	4.7	5.1	5.4	5.6	5.8	5.9	6.1	6.2	6.6	6.8	7.0
100	4.5	4.9	5.2	5.4	5.6	5.8	5.9	6.0	6.4	6.6	6.8
125	4.3	4.7	5.0	5.2	5.4	5.6	5.8	5.9	6.3	6.5	6.7
150	4.1	4.6	4.9	5.1	5.3	5.4	5.6	5.7	6.2	6.4	6.6
175	4.0	4.4	4.7	4.9	5.1	5.3	5.5	5.6	6.0	6.3	6.4
200	4.0	4.2	4.5	4.8	5.0	5.2	5.3	5.5	5.9	6.1	6.3
225	4.0	4.0	4.3	4.6	4.8	5.0	5.2	5.3	5.8	6.0	6.2
250	4.0	4.0	4.1	4.4	4.7	4.9	5.1	5.2	5.7	5.9	6.1
275	4.0	4.0	4.0	4.2	4.5	4.7	4.9	5.1	5.5	5.8	6.0
300	4.0	4.0	4.0	4.0	4.3	4.5	4.7	4.9	5.4	5.7	5.9
325	4.0	4.0	4.0	4.0	4.0	4.3	4.5	4.7	5.3	5.5	5.8
350	4.0	4.0	4.0	4.0	4.0	4.0	4.2	4.5	5.1	5.4	5.6
375	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.1	5.0	5.3	5.5
400	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.8	5.1	5.4

Table 4.7.2 Minimum Pavement Thickness for 10% Trucks

k (pci)	ADT 500	750	1000	1250	1500	1750	2000	2250	2500	3000	3500
50	5.6	6.0	6.3	6.8	7.0	7.2	7.3	7.5	7.6	7.8	8.0
75	5.4	5.8	6.1	6.6	6.8	7.0	7.2	7.3	7.4	7.7	7.8
100	5.2	5.6	5.9	6.4	6.6	6.8	7.0	7.1	7.3	7.5	7.7
125	5.0	5.4	5.8	6.3	6.5	6.7	6.9	7.0	7.1	7.4	7.6
150	4.9	5.3	5.6	6.2	6.4	6.6	6.7	6.9	7.0	7.2	7.4
175	4.7	5.1	5.5	6.0	6.3	6.4	6.6	6.8	6.9	7.1	7.3
200	4.5	5.0	5.3	5.9	6.1	6.3	6.5	6.6	6.8	7.0	7.2
225	4.3	4.8	5.2	5.8	6.0	6.2	6.4	6.5	6.7	6.9	7.1
250	4.1	4.7	5.1	5.7	5.9	6.1	6.3	6.4	6.6	6.8	7.0
275	4.0	4.5	4.9	5.5	5.8	6.0	6.2	6.3	6.5	6.7	6.9
300	4.0	4.3	4.7	5.4	5.7	5.9	6.1	6.2	6.4	6.6	6.9
325	4.0	4.0	4.5	5.3	5.5	5.8	6.0	6.1	6.3	6.5	6.8
350	4.0	4.0	4.2	5.1	5.4	5.6	5.8	6.0	6.2	6.4	6.7
375	4.0	4.0	4.0	5.0	5.3	5.5	5.7	5.9	6.1	6.3	6.6
400	4.0	4.0	4.0	4.8	5.1	5.4	5.6	5.8	6.0	6.2	6.5

Table 4.7.3 Minimum Pavement Thickness for 15% Trucks

k (pci)	ADT 500	750	1000	1250	1500	1750	2000	2250	2500	3000	3500
50	6.0	6.4	7.0	7.3	7.5	7.7	7.8	8.0	> 8	> 8	> 8
75	5.8	6.2	6.8	7.1	7.3	7.5	7.7	7.8	8.0	> 8	> 8
100	5.6	6.0	6.6	6.9	7.1	7.3	7.5	7.7	7.8	> 8	> 8
125	5.4	5.9	6.5	6.8	7.0	7.2	7.4	7.5	7.7	> 8	> 8
150	5.3	5.7	6.4	6.6	6.9	7.1	7.2	7.4	7.5	7.9	> 8
175	5.1	5.6	6.3	6.5	6.8	7.0	7.1	7.3	7.4	7.8	> 8
200	5.0	5.5	6.1	6.4	6.6	6.9	7.0	7.2	7.3	7.7	8.0
225	4.8	5.3	6.0	6.3	6.5	6.7	6.9	7.1	7.2	7.6	7.9
250	4.7	5.2	5.9	6.2	6.4	6.6	6.8	7.0	7.1	7.6	7.8
275	4.5	5.1	5.8	6.1	6.3	6.5	6.7	6.9	7.0	7.5	7.7
300	4.3	4.9	5.7	6.0	6.2	6.4	6.6	6.8	6.9	7.4	7.6
325	4.0	4.7	5.5	5.9	6.1	6.3	6.5	6.7	6.9	7.3	7.5
350	4.0	4.5	5.4	5.7	6.0	6.2	6.4	6.6	6.8	7.2	7.4
375	4.0	4.1	5.3	5.6	5.9	6.1	6.3	6.5	6.7	7.1	7.4
400	4.0	4.0	5.1	5.5	5.8	6.0	6.2	6.4	6.6	7.1	7.3

Table 4.7.4 Minimum Pavement Thickness for 20% Trucks

	ADT										
k (pci)	500	750	1000	1250	1500	1750	2000	2250	2500	3000	3500
50	6.3	7.0	7.3	7.6	7.8	8.0	> 8	> 8	> 8	> 8	> 8
75	6.1	6.8	7.2	7.4	7.7	7.8	> 8	> 8	> 8	> 8	> 8
100	5.9	6.6	7.0	7.3	7.5	7.7	8.0	> 8	> 8	> 8	> 8
125	5.8	6.5	6.9	7.1	7.4	7.6	7.9	> 8	> 8	> 8	> 8
150	5.6	6.4	6.7	7.0	7.2	7.4	7.8	7.9	> 8	> 8	> 8
175	5.5	6.3	6.6	6.9	7.1	7.3	7.7	7.8	8.0	> 8	> 8
200	5.3	6.1	6.5	6.8	7.0	7.2	7.6	7.7	7.9	> 8	> 8
225	5.2	6.0	6.4	6.7	6.9	7.1	7.5	7.6	7.8	> 8	> 8
250	5.1	5.9	6.3	6.6	6.8	7.0	7.4	7.6	7.7	8.0	> 8
275	4.9	5.8	6.2	6.5	6.7	6.9	7.3	7.5	7.6	7.9	> 8
300	4.7	5.0	6.1	6.4	6.6	6.9	7.2	7.4	7.5	7.8	8.0
325	4.5	5.5	6.0	6.3	6.5	6.8	7.1	7.3	7.5	7.7	8.0
350	4.2	5.4	5.8	6.2	6.4	6.7	7.0	7.2	7.4	7.6	7.9
375	4.0	5.3	5.7	6.1	6.3	6.6	7.0	7.1	7.3	7.6	7.8
400	4.0	5.1	5.6	6.0	6.2	6.5	6.9	7.0	7.2	7.5	7.7

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Errors of the past will dictate designs of the future. Unfortunately there is not a precise recipe for pervious concrete that will yield a high compressive strength and porosity. Testing along with analysis of existing systems is the best method for developing a range of values which will lead to a functional design.

Relying on the analysis of existing parking lots, the use of pervious concrete should be limited to areas not subjected to high volumes of traffic; one of the parking lots investigated was subjected to approximately 213,000 of vehicles trips per year. Raveling of the pervious concrete is limited to the entrance and exit points of parking areas. Therefore areas subjected to high volumes should not be constructed of pervious concrete but either asphalt or conventional concrete. Another concern is maintenance vehicles such as garbage trucks. Although existing parking lots are able to withstand these vehicles driving through the lot, that portion of the pavement where these vehicles load and unload is heavily damaged. Recommendations are that pervious concrete should not be placed in areas subjected to repeated heavy loads.

Testing of pervious concrete provides additional information as to selecting appropriate ratios. An A/C ratio less than 5 in combination with a W/C ratio in the range of 0.35 – 0.39 provided the highest compressive strength without jeopardizing permeability.

Higher A/C ratios do not supply enough cement and higher W/C ratios tend to eliminate void spaces.

Another aspect is compaction energy. The energy applied to the pervious concrete utilizing the modified Proctor compaction method was approximately 1544 kN-m/m^3. The higher compaction energy was not detrimental to the porosity but did allow the compressive strength to increase.

Even though the compressive strength of the pervious concrete is considerably less than that of conventional concrete, the strengths achieved would be able to sustain loadings from vehicles ranging from automobiles to tractor trailers up to 80,000 lbs. All of the mixtures tested, however, did not attain compressive strength strong enough to sustain such high vehicle loadings. On the other hand a couple of the mixtures would be able to sustain higher vehicle loadings in the order of 100,000 lbs. Recommendations are that pervious concrete be limited to areas that are subjected to small vehicle loads with occasional use by larger vehicles.

Pavement thickness design is dependent on several factors. Those include the quality of the subgrade, the compressive strength on the pavement, and the traffic loadings on the pavement. Without accurate traffic counts or knowledge of the type of soil used it is difficult to develop exact design numbers. The tables provided in this thesis are meant to be used as a guideline. They do however illustrate the effect increasing the volume, loading, or quality of subgrade has on the minimum thickness required for an adequate design.

Pervious concrete, although not as strong as conventional concrete, provides an acceptable alternative when used in low volume and low impact areas. Strength is sacrificed for permeability but not to any degree which would render the pervious concrete not functional.

5.2 Recommendations for Future Research

There are several areas that need to be addressed in future research. The aggregate used in this study was limited to one type and size. Larger and harder aggregate should provide a higher compressive strength, the effect on porosity and permeability rates would have to be studied.

The A/C ratios used in this research ranged from 4:1 to 7:1. Those mixtures with the higher ratios, 6:1 and 7:1, were deemed unacceptable due to their low compressive strengths. This should provide a good starting point for future research. More research should limit the A/C ratios to less than 5:1; even attempting ratios as low as 2:1. With such high permeability rates obtained, it is reasonable to assume that lower A/C ratios would still proved acceptable levels of permeability.

Compaction energy should also be considered. The Modified Proctor compaction test provided a high level of energy but higher levels should be tested and compared. Again considering the high rates of permeability, more compaction of the pervious concrete should not be detrimental.

Accurate traffic studies should be conducted. Time constraints limited the traffic analysis in this research to estimates. Existing sites should be thoroughly evaluated for volume and loadings for all days of the week and for all hours in order to provide a more accurate representation of what the pervious concrete is subjected to on a daily basis. The research conducted for the purpose of this thesis cannot be considered extensive. Although it encompasses a diverse amount of variables, there is room for much more research. The data provided, however, can be a useful tool for future research and pervious concrete design.

Finally, pavement thickness design is area which was only briefly investigated in this thesis. Future research in this matter needs to be explored. Exact traffic volumes and loadings should be determined for a variety of businesses. Obviously the more exact data available for design the more accurate the solution.

APPENDIX A: CALCULATIONS

Compaction Energy – Standard Proctor Compaction Test

$$E = \frac{(\text{Blows / layer})(\text{Layers})(\text{Weight})(\text{Height})}{\text{Volume}}$$

$$E = \frac{(25)(3)(5.5\text{lb})(1\text{ft})}{0.0581776\text{ft}^3} = 7090\,\frac{\text{ft}\bullet\text{lb}}{\text{ft}^3}$$

$$E = \frac{(25)(3)\left(\frac{(2.5\text{kg})(9.81)}{1000}\text{kN}\right)(0.305\text{m})}{0.00164741\text{m}^3} = 341\frac{\text{kN}\bullet\text{m}}{\text{m}^3}$$

Compaction Energy – Modified Proctor Compaction Test

$$E = \frac{(\text{Blows / layer})(\text{Layers})(\text{Weight})(\text{Height})}{\text{Volume}}$$

$$E = \frac{(25)(5)(10\text{lb})(1.5\text{ft})}{0.0581776\text{ft}^3} = 32229\,\frac{\text{ft}\bullet\text{lb}}{\text{ft}^3}$$

$$E = \frac{(25)(5)\left(\frac{(4.54\text{kg})(9.81)}{1000}\text{kN}\right)(0.457\text{m})}{0.00164741\text{m}^3} = 1544\,\frac{\text{kN}\bullet\text{m}}{\text{m}^3}$$

Calculations for FC&PA Office

$$\left(\frac{6\text{vehicles}}{\text{day}}\right)\left(\frac{5\text{days}}{\text{week}}\right)\left(\frac{52\text{weeks}}{\text{year}}\right)=1560\frac{\text{vehicles}}{\text{year}}$$

Calculations for Sun Ray Store Away

Weekday

$$T=\left(\frac{3.245}{x}+0.00129\right)^{-1}$$

$$T=\left(\frac{3.245}{823}+0.00129\right)^{-1}$$

$$T=191\frac{\text{vehicles}}{\text{day}}$$

$$\left(\frac{191\text{vehicles}}{\text{day}}\right)\left(\frac{5\text{days}}{\text{week}}\right)\left(\frac{52\text{weeks}}{\text{year}}\right)=49{,}660\frac{\text{vehicles}}{\text{year}}$$

Saturday

$$T=\left(\frac{6.008}{x}-0.00242\right)^{-1}$$

$$T=\left(\frac{6.008}{823}-0.00242\right)^{-1}$$

$$T=205\frac{\text{vehicles}}{\text{day}}$$

$$\left(\frac{205\text{vehicles}}{\text{day}}\right)\left(\frac{1\text{day}}{\text{week}}\right)\left(\frac{52\text{weeks}}{\text{year}}\right)=10{,}660\frac{\text{vehicles}}{\text{year}}$$

Sunday

$$T = \left(\frac{4.433}{x} + 0.00258\right)^{-1}$$

$$T = \left(\frac{4.433}{823} + 0.00258\right)^{-1}$$

$$T = 126\,\frac{\text{vehicles}}{\text{day}}$$

$$\left(\frac{126\text{vehicles}}{\text{day}}\right)\left(\frac{1\text{day}}{\text{week}}\right)\left(\frac{52\text{weeks}}{\text{year}}\right) = 6{,}552\,\frac{\text{vehicles}}{\text{year}}$$

$$\left(49{,}660\,\frac{\text{vehicles}}{\text{year}}\right) + \left(10{,}660\,\frac{\text{vehicles}}{\text{year}}\right) + \left(6{,}552\,\frac{\text{vehicles}}{\text{year}}\right) = 66{,}872\,\frac{\text{vehicles}}{\text{year}}$$

Calculations for Strang Communications

$$\ln T = 0.756 \ln x + 2.701$$

$$\ln T = 0.756 \ln(200) + 2.701$$

$$T = 820\,\frac{\text{vehicles}}{\text{day}}$$

$$\left(\frac{820\text{vehicles}}{\text{day}}\right)\left(\frac{5\text{days}}{\text{week}}\right)\left(\frac{52\text{weeks}}{\text{year}}\right) = 213{,}200\,\frac{\text{vehicles}}{\text{year}}$$

Calculations for Murphy Veterinary Clinic

$$\left(\frac{4 \text{ employee vehicles}}{\text{day}}\right)\left(\frac{6 \text{ days}}{\text{week}}\right)\left(\frac{52 \text{ weeks}}{\text{year}}\right) = 1{,}248 \frac{\text{employee vehicles}}{\text{year}}$$

$$\left(\frac{4 \text{ patient vehicles}}{\text{hour}}\right)\left(\frac{8 \text{ hours}}{\text{day}}\right)\left(\frac{6 \text{ days}}{\text{week}}\right)\left(\frac{52 \text{ weeks}}{\text{year}}\right) = 9{,}984 \frac{\text{patient vehicles}}{\text{year}}$$

$$\left(1{,}248 \frac{\text{employee vehicles}}{\text{year}}\right) + \left(9{,}984 \frac{\text{patient vehicles}}{\text{year}}\right) = 11{,}232 \frac{\text{vehicles}}{\text{year}}$$

Calculations for Dental Office

$$\left(\frac{5 \text{ employee vehicles}}{\text{day}}\right)\left(\frac{5 \text{ days}}{\text{week}}\right)\left(\frac{52 \text{ weeks}}{\text{year}}\right) = 1{,}300 \frac{\text{employee vehicles}}{\text{year}}$$

$$\left(\frac{4 \text{ patient vehicles}}{\text{hour}}\right)\left(\frac{8 \text{ hours}}{\text{day}}\right)\left(\frac{5 \text{ days}}{\text{week}}\right)\left(\frac{52 \text{ weeks}}{\text{year}}\right) = 8{,}320 \frac{\text{patient vehicles}}{\text{year}}$$

$$\left(1{,}300 \frac{\text{employee vehicles}}{\text{year}}\right) + \left(8{,}320 \frac{\text{patient vehicles}}{\text{year}}\right) = 9{,}620 \frac{\text{vehicles}}{\text{year}}$$

APPENDIX B: ITE TRIP GENERATION MANUAL GRAPHS

Mini-Warehouse
(151)

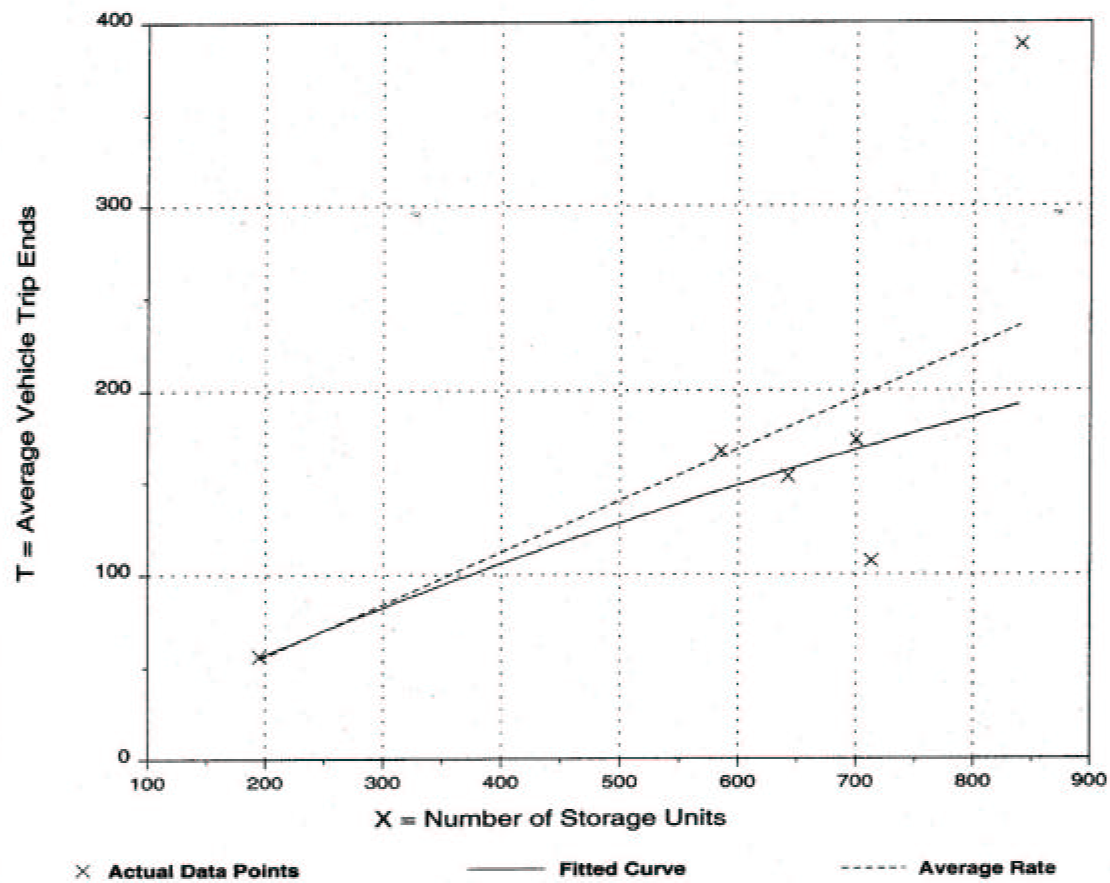
Average Vehicle Trip Ends vs: Storage Units
On a: Weekday

Number of Studies: 6
Average Number of Storage Units: 613
Directional Distribution: 50% entering, 50% exiting

Trip Generation per Storage Unit

Average Rate	Range of Rates	Standard Deviation
0.28	0.15 - 0.46	0.54

Data Plot and Equation



Fitted Curve Equation: $T = [(3.245/X) + 0.00129]^{-1}$ $R^2 = 0.86$

Mini-Warehouse
(151)

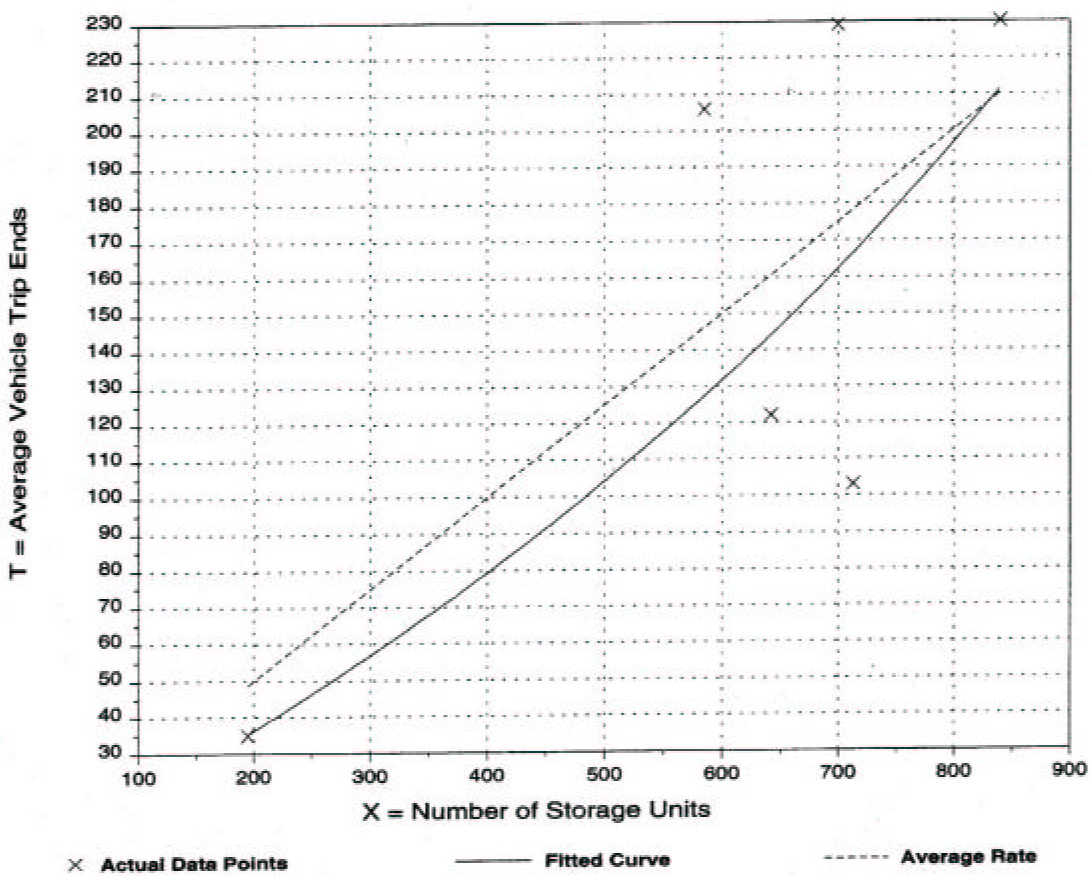
Average Vehicle Trip Ends vs: Storage Units
On a: Saturday

Number of Studies: 6
Average Number of Storage Units: 613
Directional Distribution: 50% entering, 50% exiting

Trip Generation per Storage Unit

Average Rate	Range of Rates	Standard Deviation
0.25	0.14 - 0.35	0.51

Data Plot and Equation



Fitted Curve Equation: $T = [(6.008/X) - 0.00242]^{-1}$ $R^2 = 0.94$

Mini-Warehouse
(151)

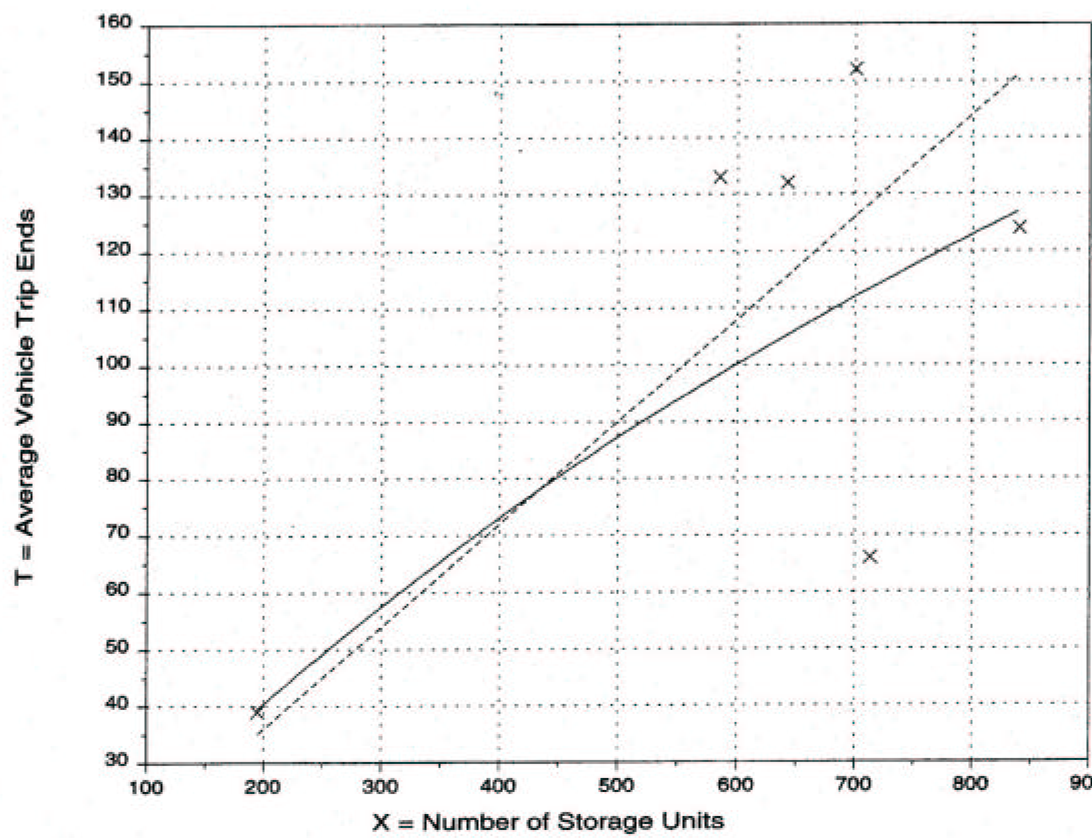
Average Vehicle Trip Ends vs: Storage Units
On a: Sunday

Number of Studies: 6
Average Number of Storage Units: 613
Directional Distribution: 50% entering, 50% exiting

Trip Generation per Storage Unit

Average Rate	Range of Rates	Standard Deviation
0.18	0.09 - 0.23	0.42

Data Plot and Equation



× Actual Data Points —— Fitted Curve ------ Average Rate

Fitted Curve Equation: $T = [(4.433/X) + 0.00258]^{-1}$ $R^2 = 0.63$

Single Tenant Office Building
(715)

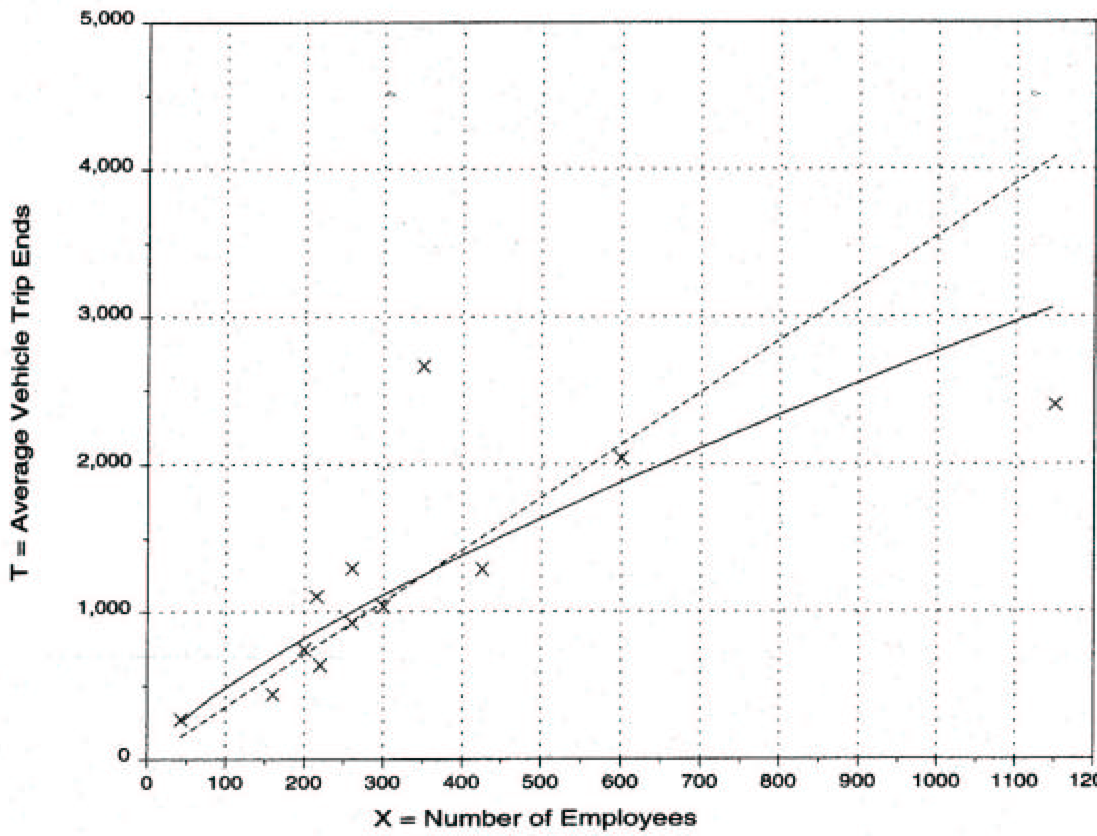
Average Vehicle Trip Ends vs: Employees
On a: Weekday

Number of Studies: 12
Average Number of Employees: 349
Directional Distribution: 50% entering, 50% exiting

Trip Generation per Employee

Average Rate	Range of Rates	Standard Deviation
3.55	2.09 - 7.61	2.43

Data Plot and Equation

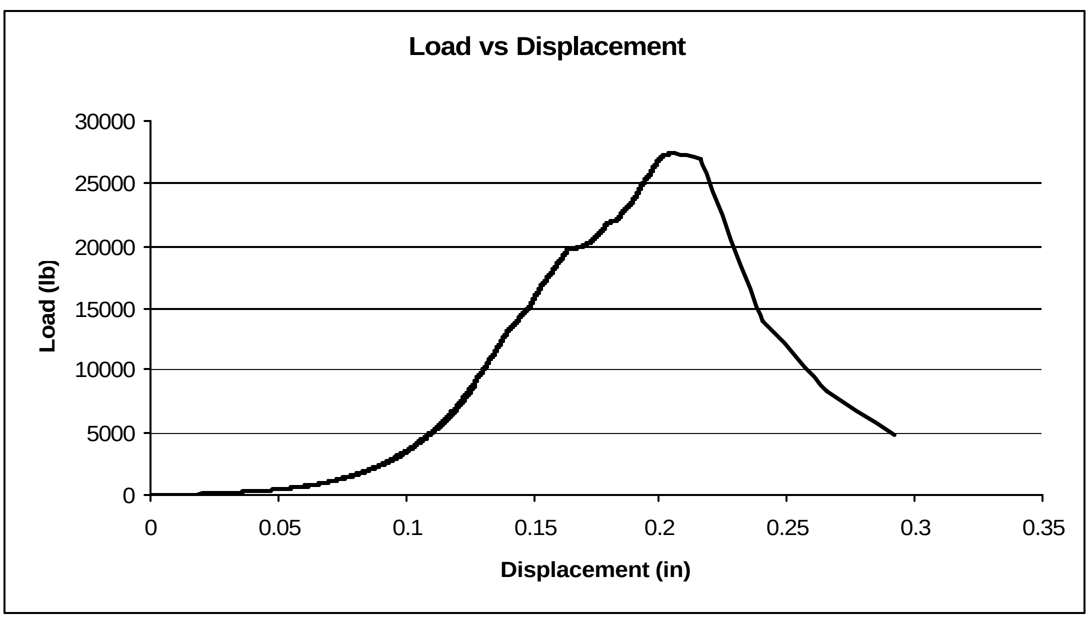


Fitted Curve Equation: Ln(T) = 0.756 Ln(X) + 2.701 $R^2 = 0.78$

APPENDIX C: TEST CYLINDER PHOTOGRAPHS AND GRAPHS

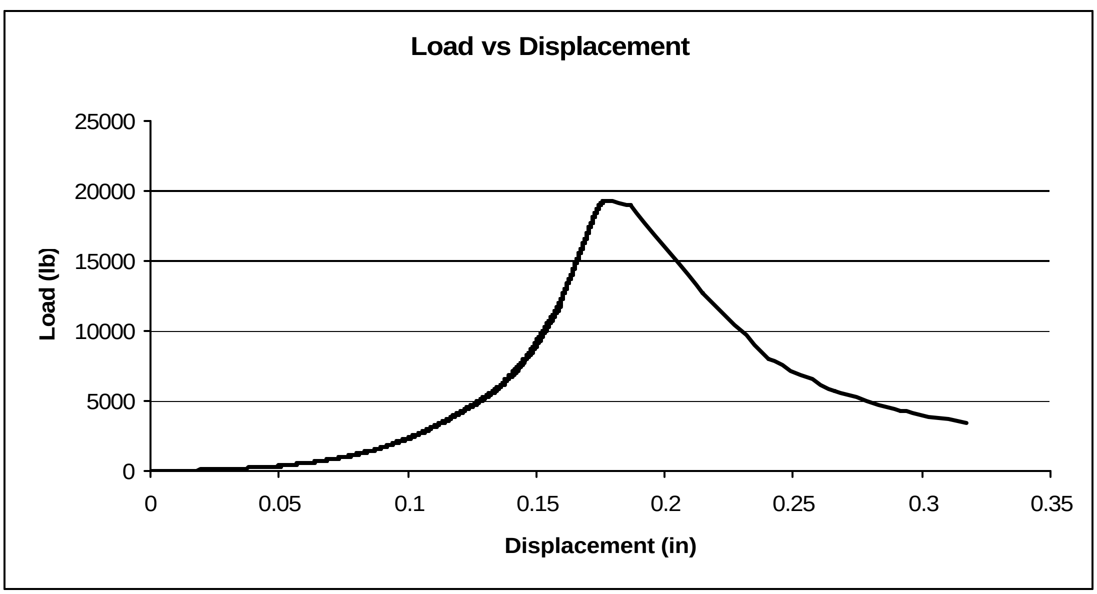

Cylinder
1111

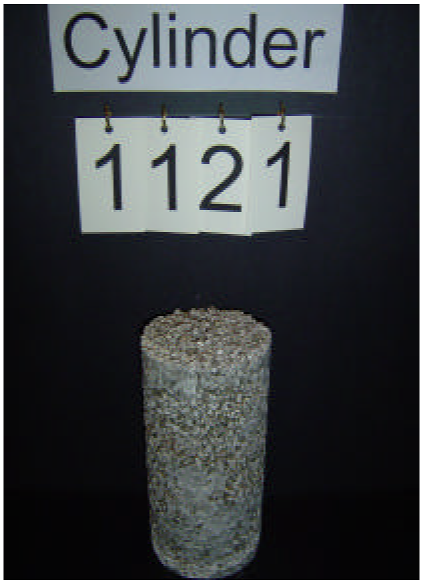

Cylinder
1111


Load vs Displacement
30000
25000
20000
15000
10000
5000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

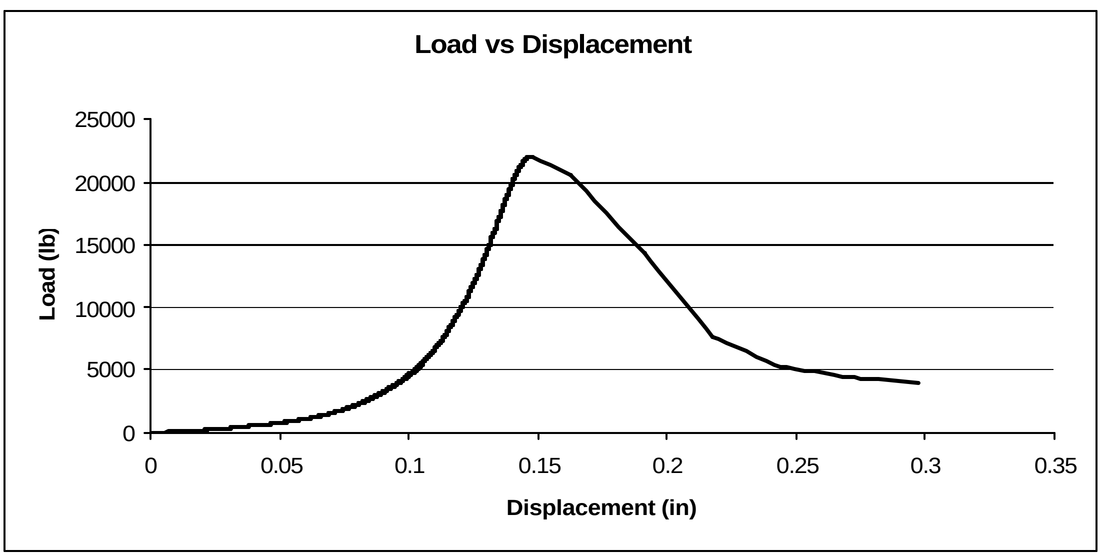

Cylinder
1112


Cylinder
1112


Load vs Displacement
Load (lb)
Displacement (in)
25000
20000
15000
10000
5000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

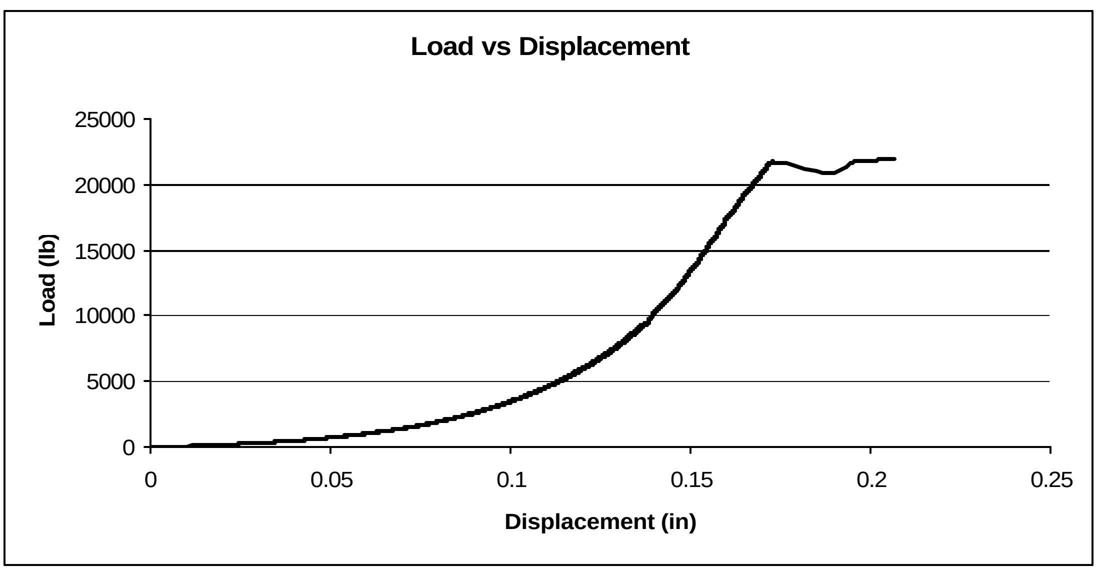

Cylinder
1121


Cylinder
1121

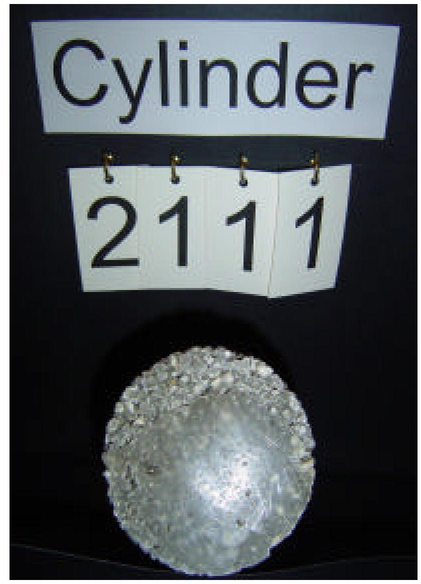

Load vs Displacement
25000
20000
15000
10000
5000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

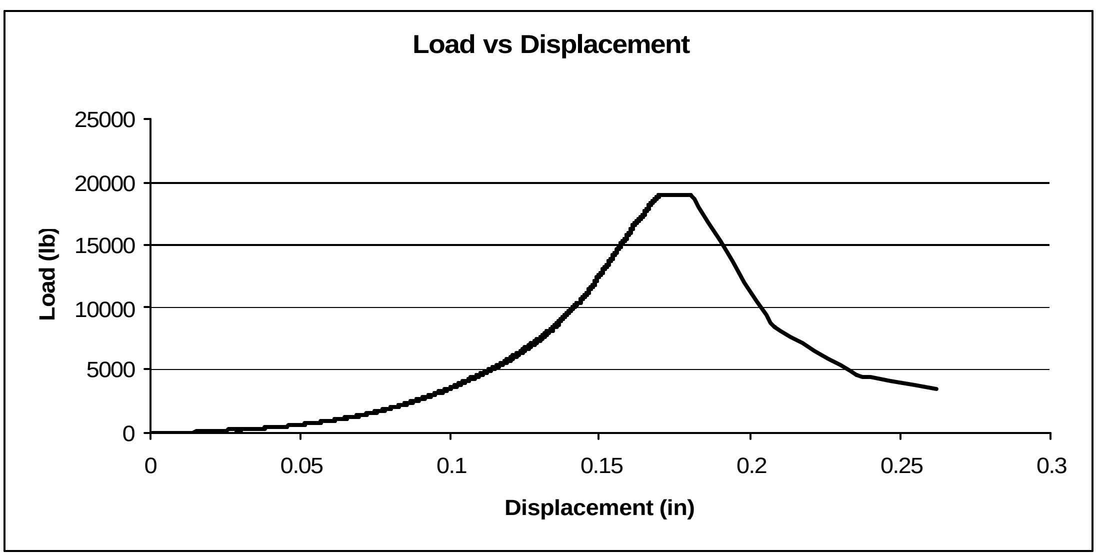

Cylinder
1122


Cylinder
1122


Load vs Displacement
25000
20000
15000
10000
5000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
Displacement (in)

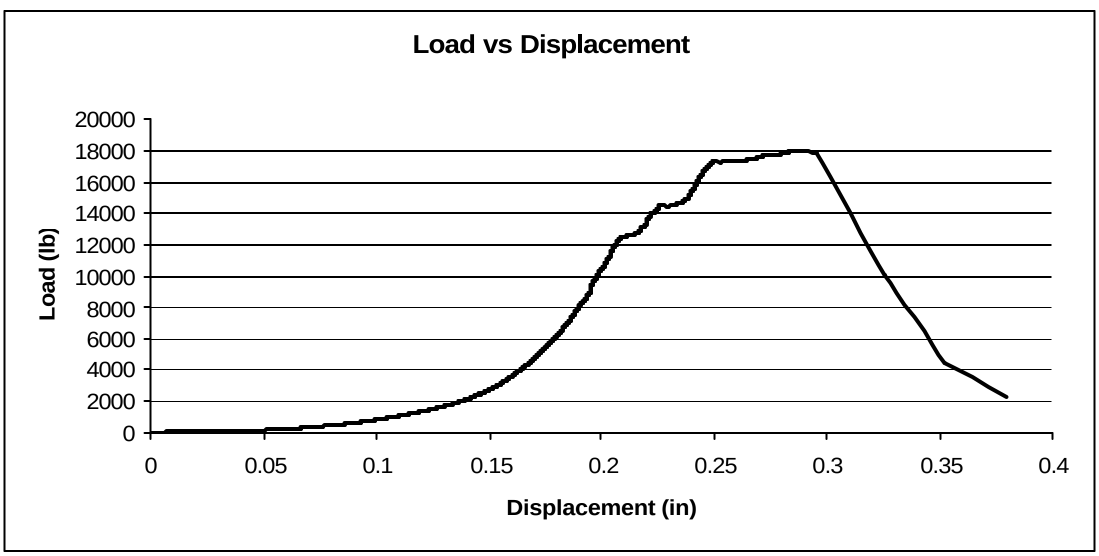

Cylinder
2111

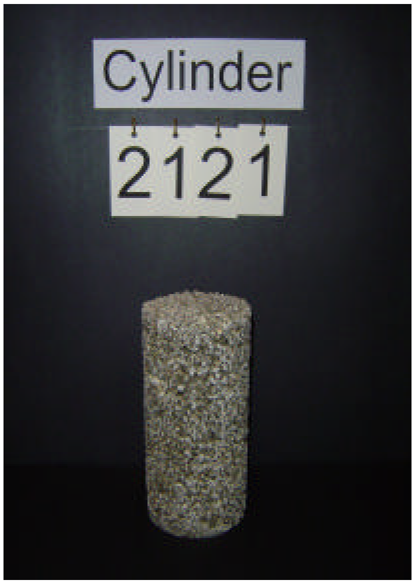

Cylinder
2111


Load vs Displacement
Load (lb)
25000
20000
15000
10000
5000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Displacement (in)

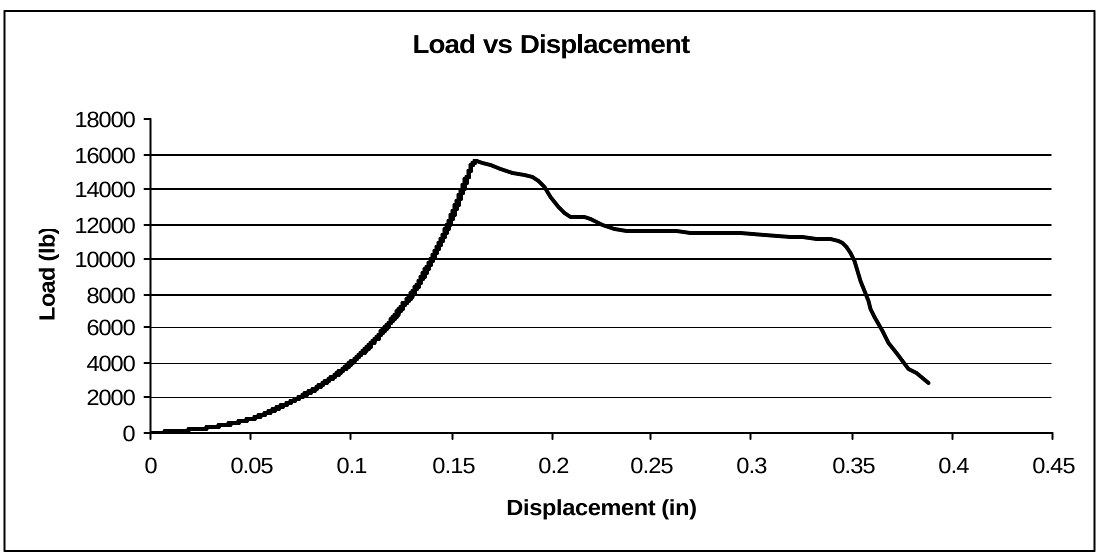

Cylinder
2112


Cylinder
2112


Load vs Displacement
Load (lb)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

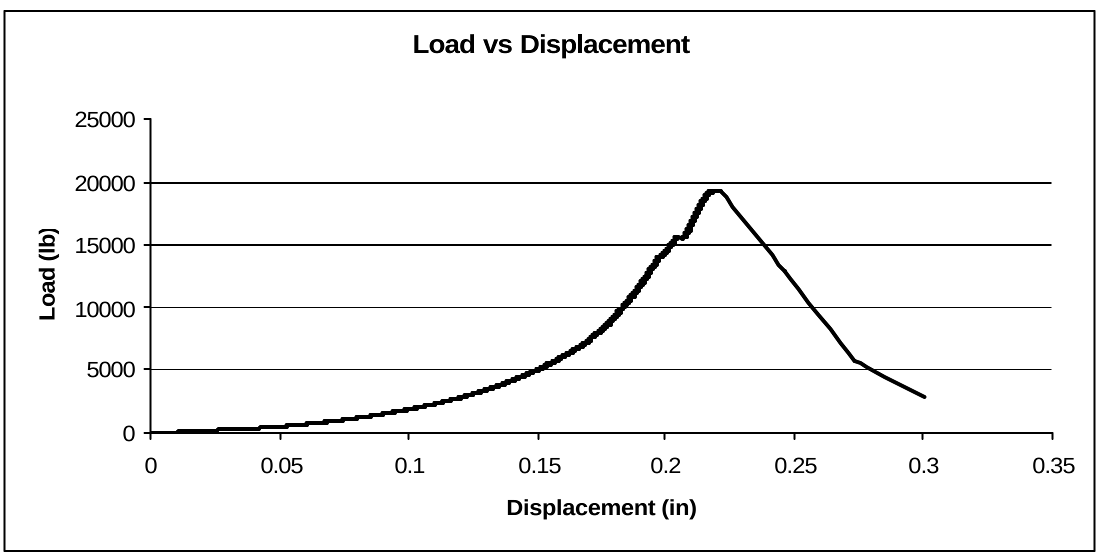

Cylinder
2121


Cylinder
2121


Load vs Displacement
Load (lb)
Displacement (in)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45

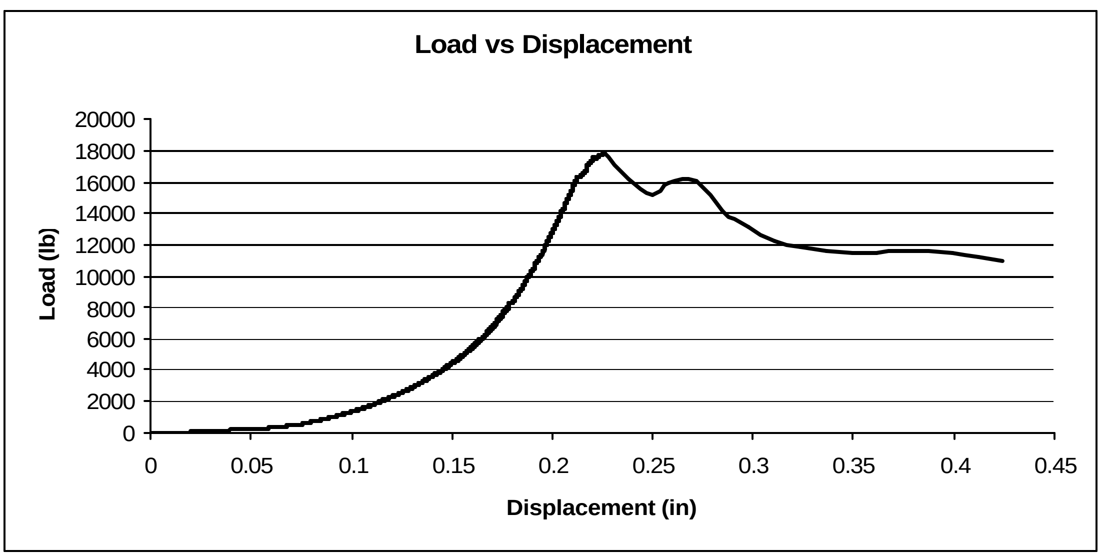

Cylinder
2122


Cylinder
2122


Load vs Displacement
Load (lb)
25000
20000
15000
10000
5000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

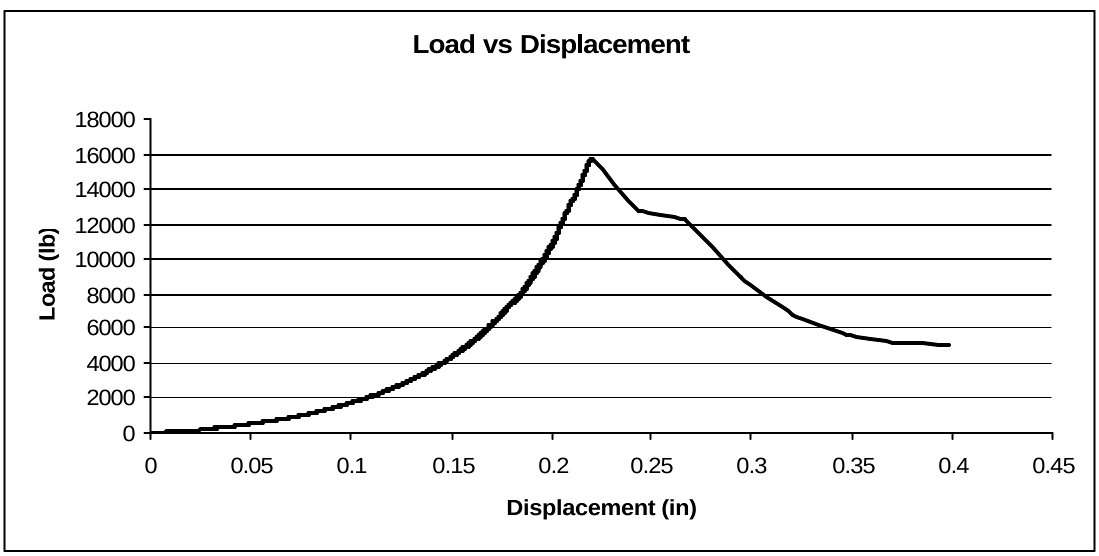

Cylinder
3211


Cylinder
3211


Load vs Displacement
Load (lb)
Displacement (in)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45

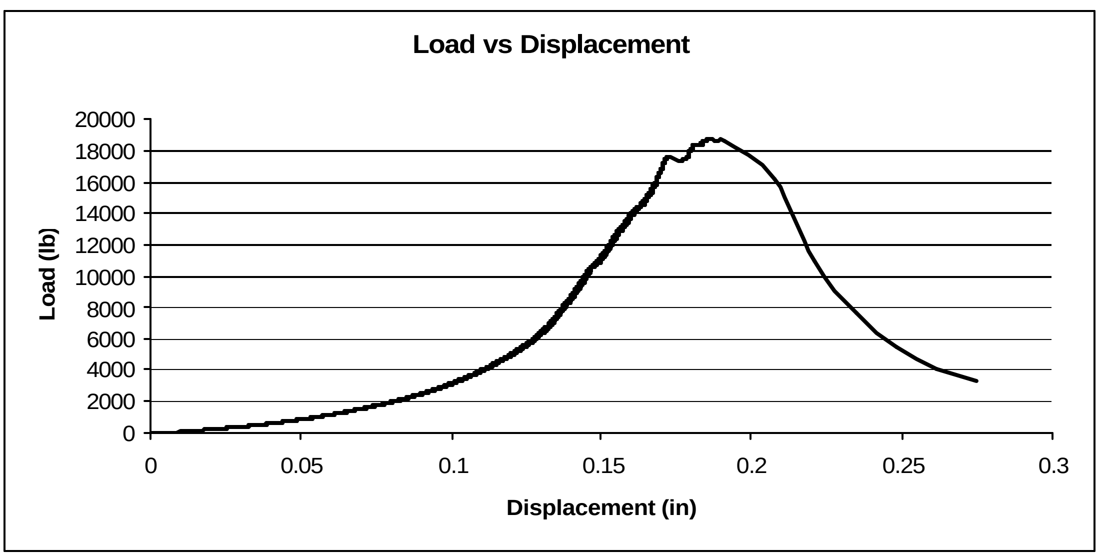

Cylinder
3212


Cylinder
3212


Load vs Displacement
Load (lb)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Displacement (in)

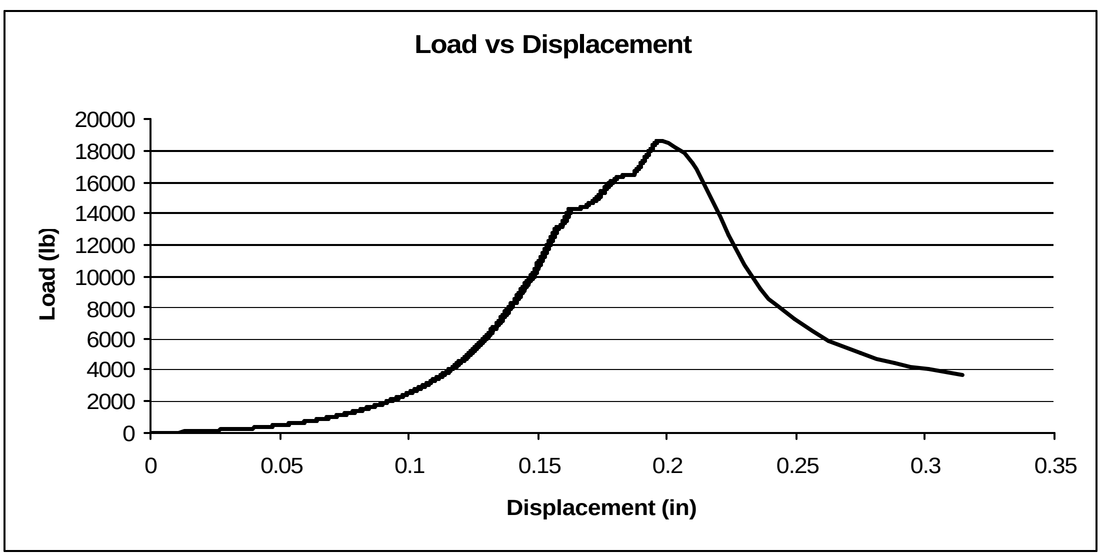

Cylinder
3221


Cylinder
3221


Load vs Displacement
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
Displacement (in)

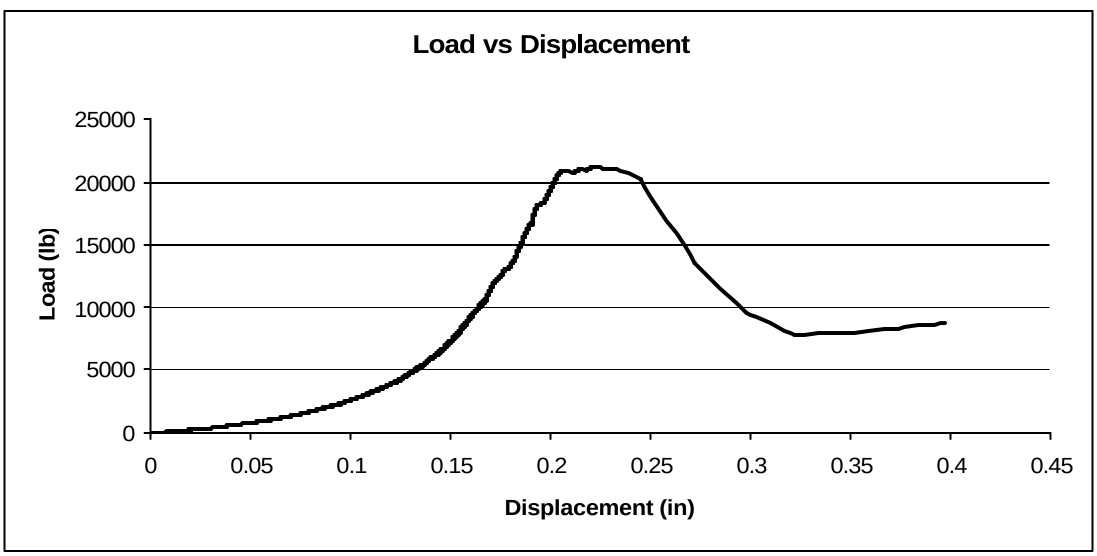

Cylinder
3222


Cylinder
3222


Load vs Displacement
Load (lb)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

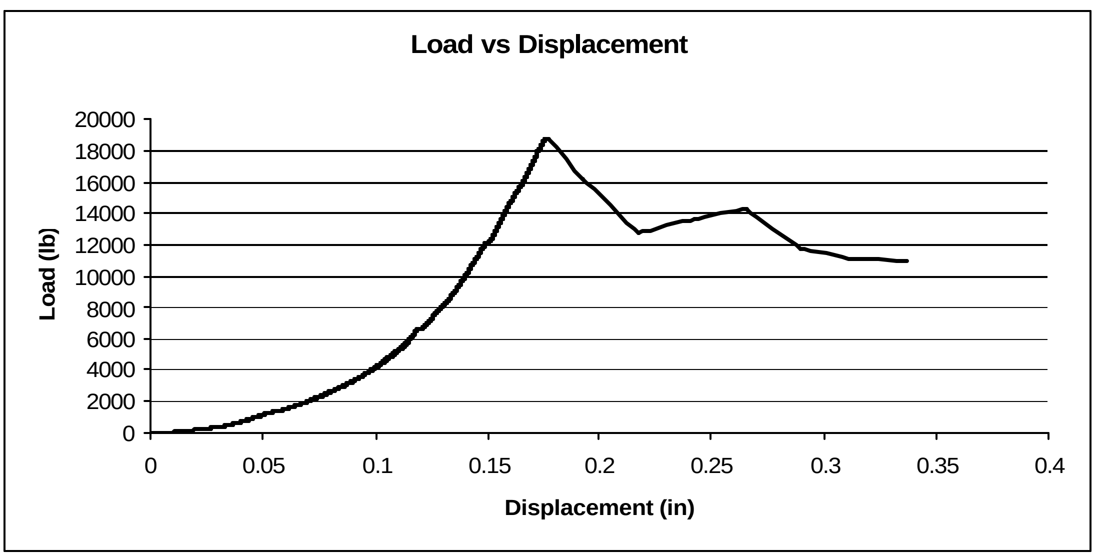

Cylinder
4211


Cylinder
4211


Load vs Displacement
25000
20000
15000
10000
5000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Displacement (in)

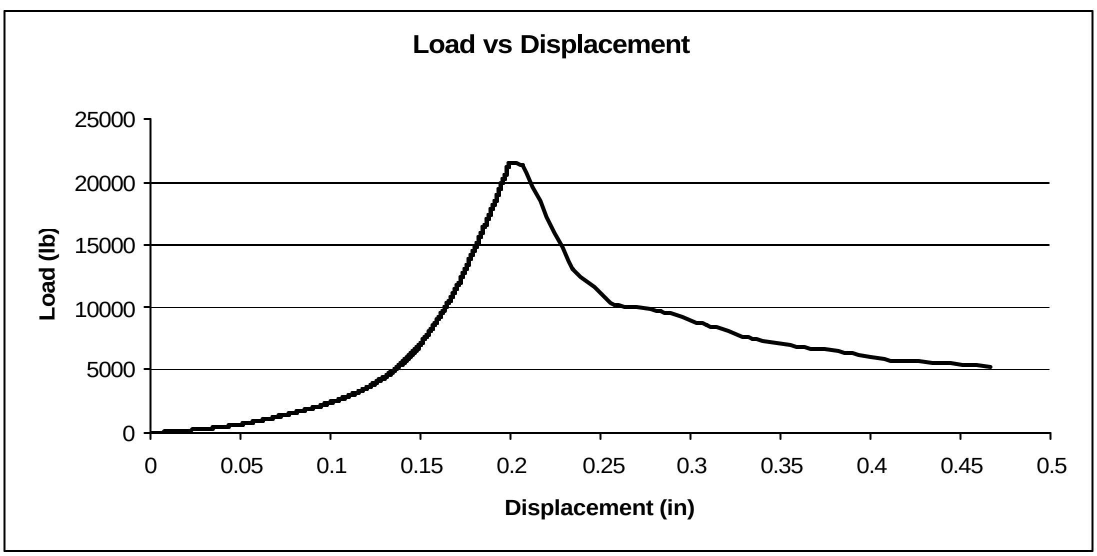

Cylinder
4212


Cylinder
4212


Load vs Displacement
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

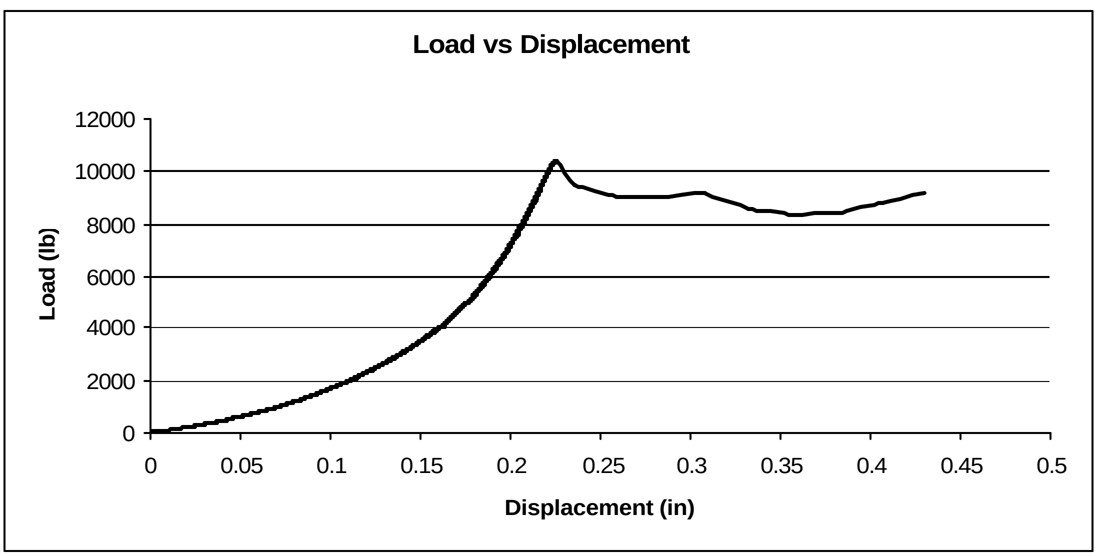

Cylinder
4221


Cylinder
4221


Load vs Displacement
25000
20000
15000
10000
5000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (in)

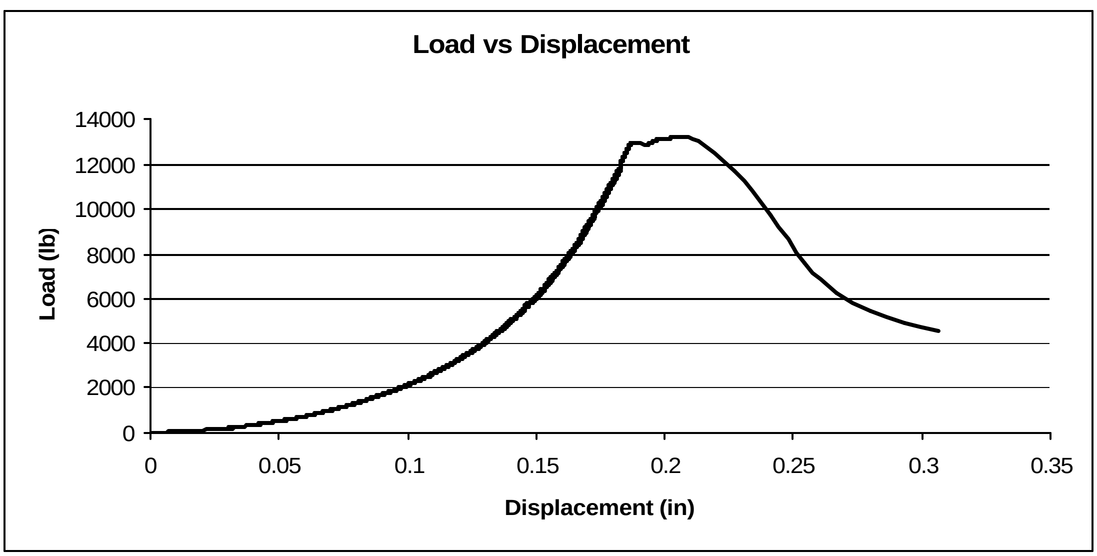

Cylinder
5311


Cylinder
5311


Load vs Displacement
Load (lb)
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Displacement (in)

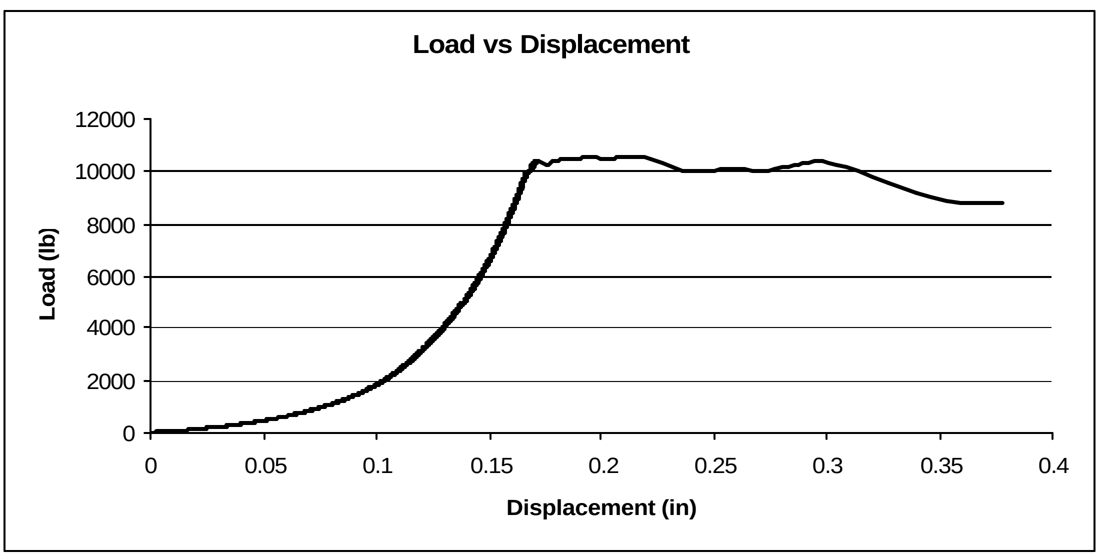

Cylinder
5312


Cylinder
5312


Load vs Displacement
Load (lb)
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

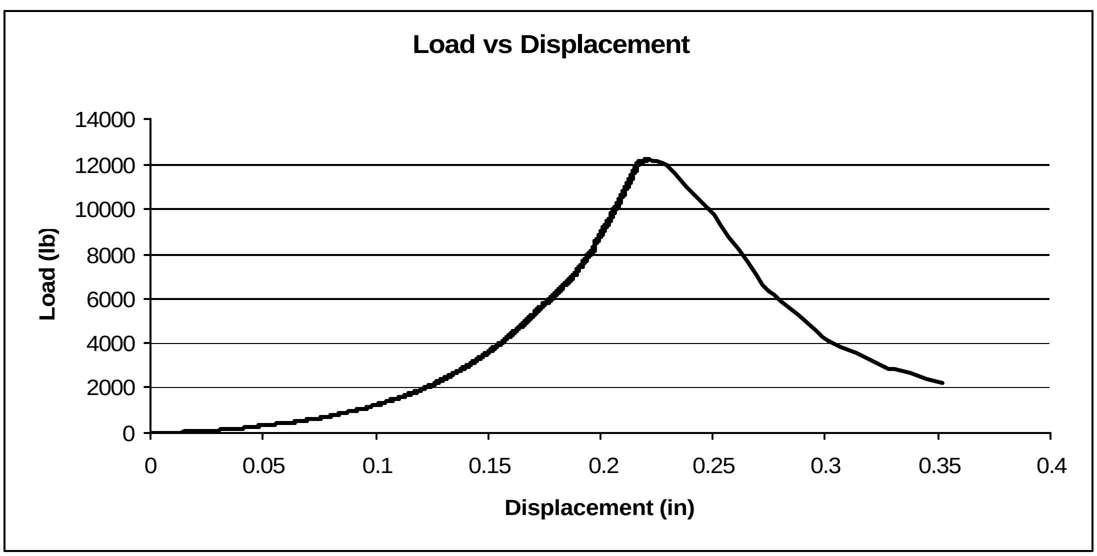

Cylinder
5321


Cylinder
5321


Load vs Displacement
Load (lb)
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

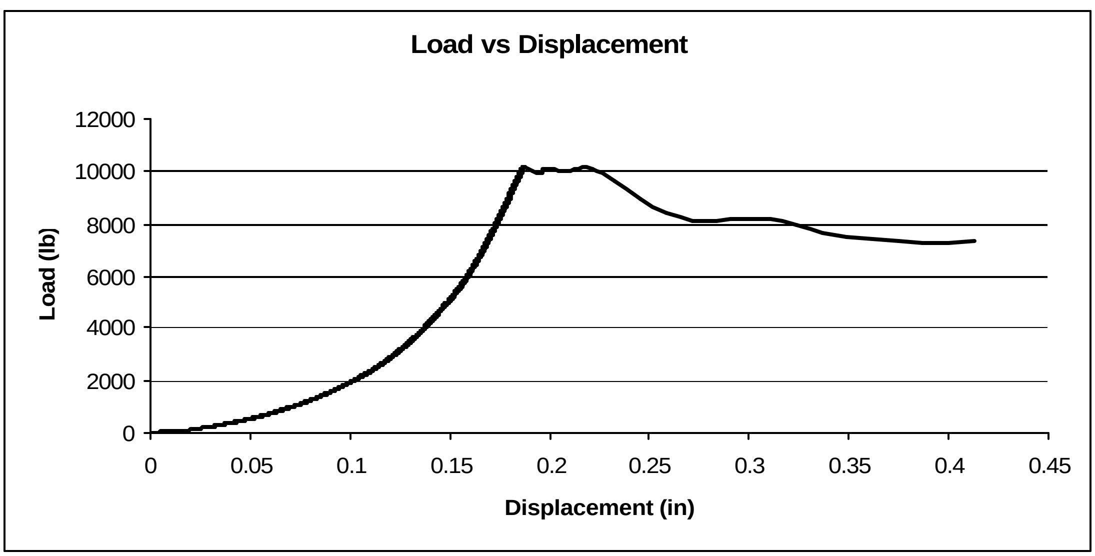

Cylinder
5322


Cylinder
5322


Load vs Displacement
Load (lb)
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

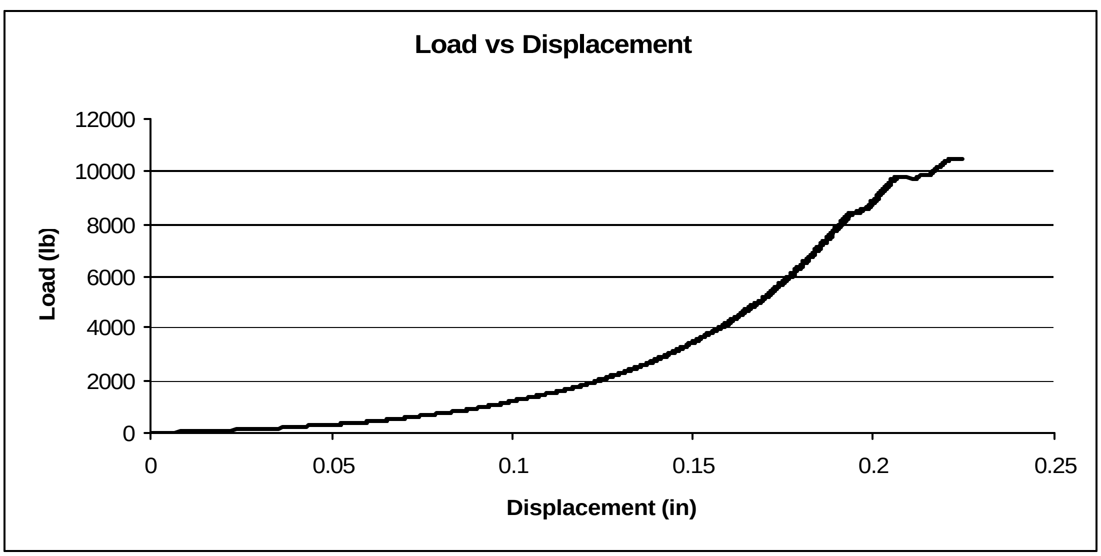

Cylinder
6311


Cylinder
6311


Load vs Displacement
Load (lb)
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Displacement (in)

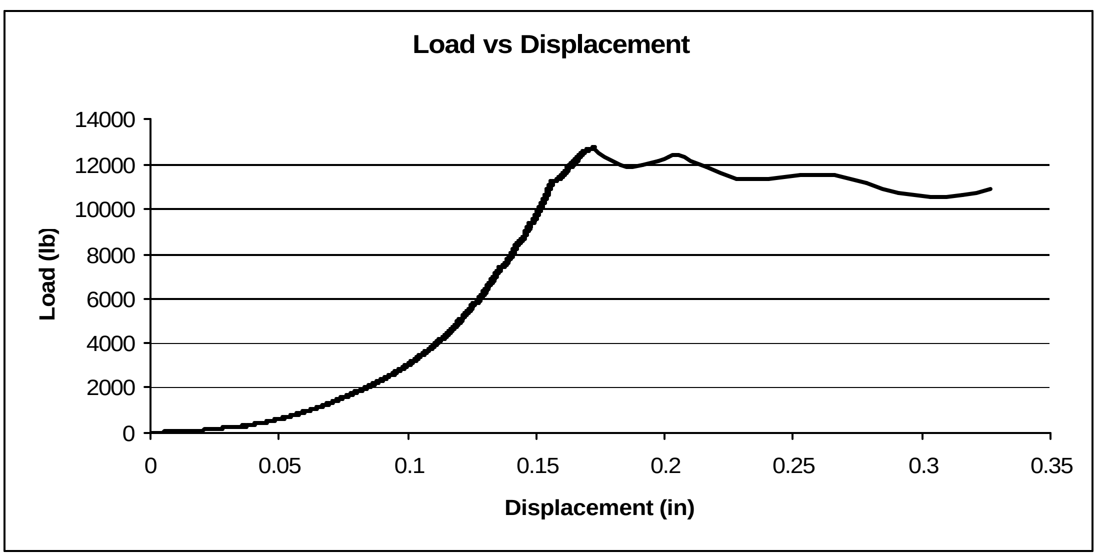

Cylinder
6312


Cylinder
6312


Load vs Displacement
Load (lb)
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
Displacement (in)

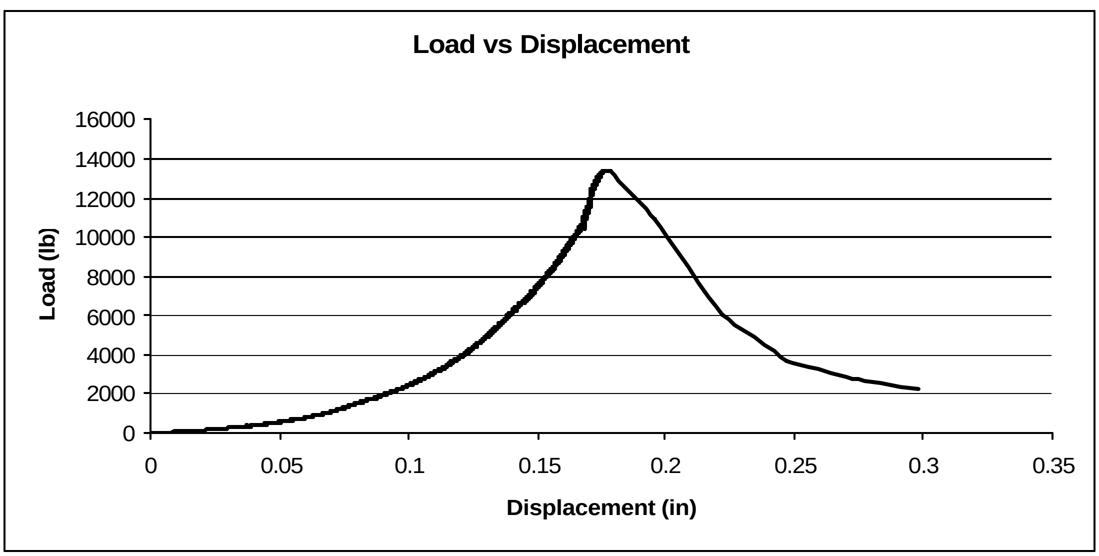

Cylinder
6321


Cylinder
6321


Load vs Displacement
14000
12000
10000
8000
6000
4000
2000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

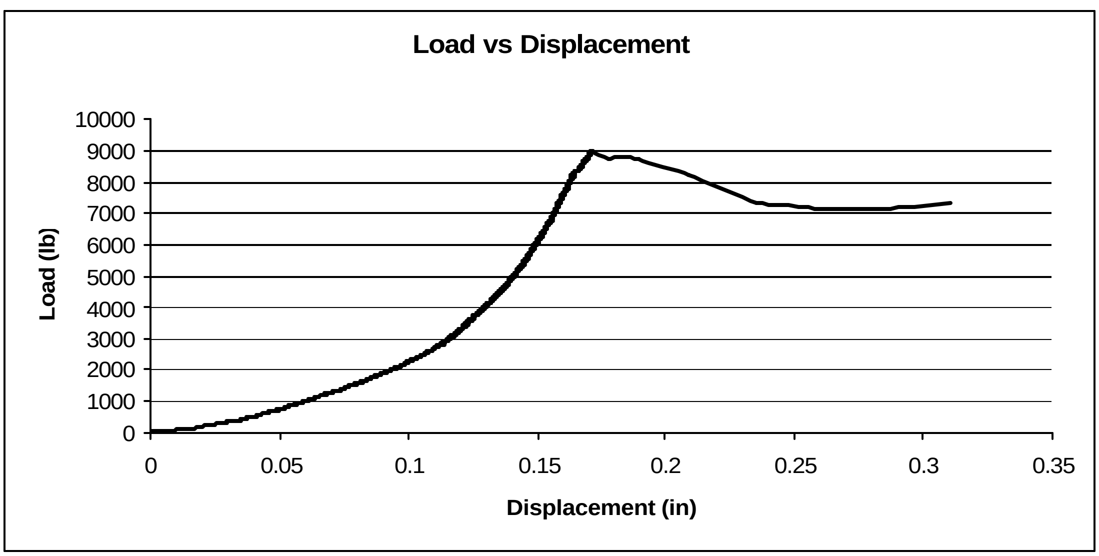

Cylinder
6322


Cylinder
6322


Load vs Displacement
16000
14000
12000
10000
8000
6000
4000
2000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Displacement (in)

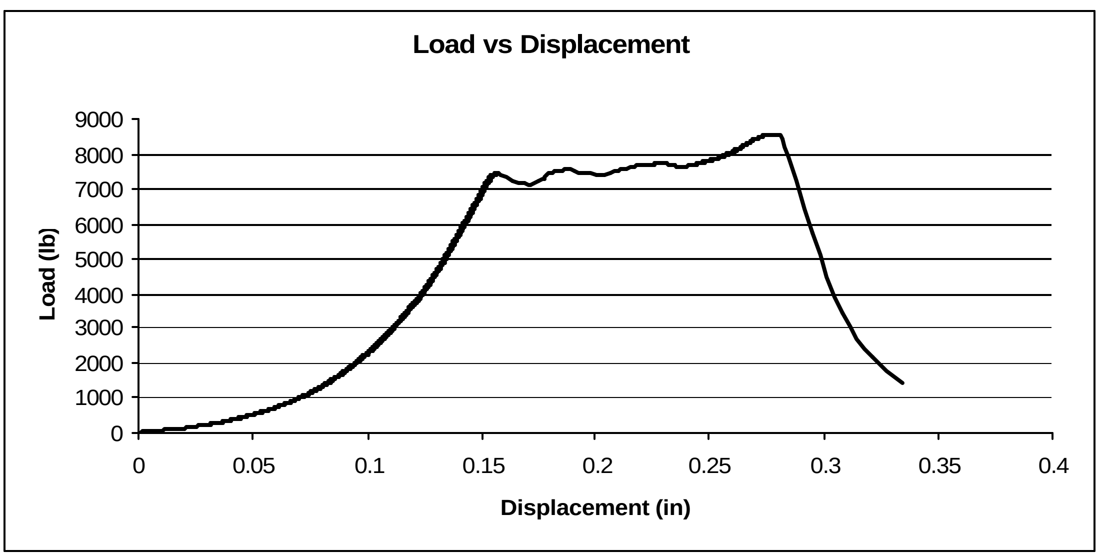

Cylinder
7411


Cylinder
7411


Load vs Displacement
Load (lb)
Displacement (in)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

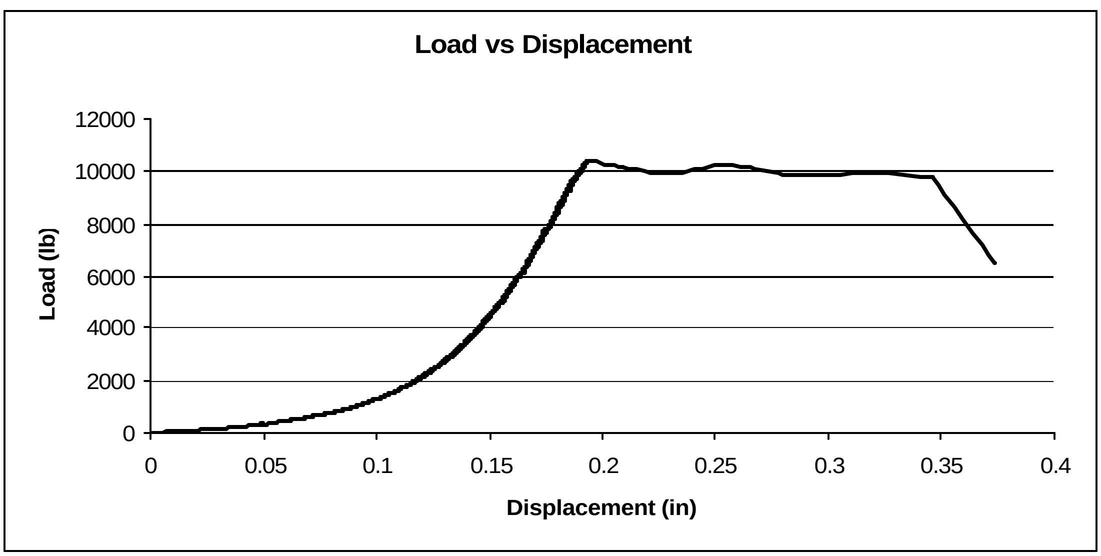

Cylinder
7412


Cylinder
7412


Load vs Displacement
Load (lb)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

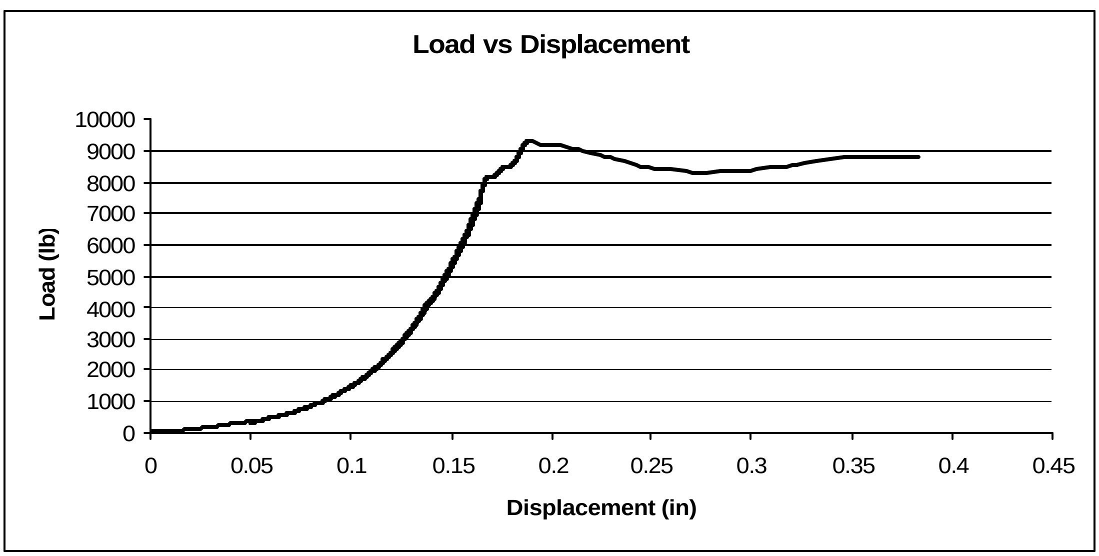

Cylinder
7421

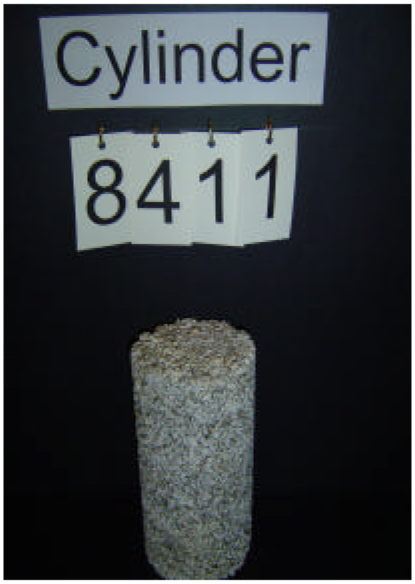

Cylinder
7421


Load vs Displacement
12000
10000
8000
6000
4000
2000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

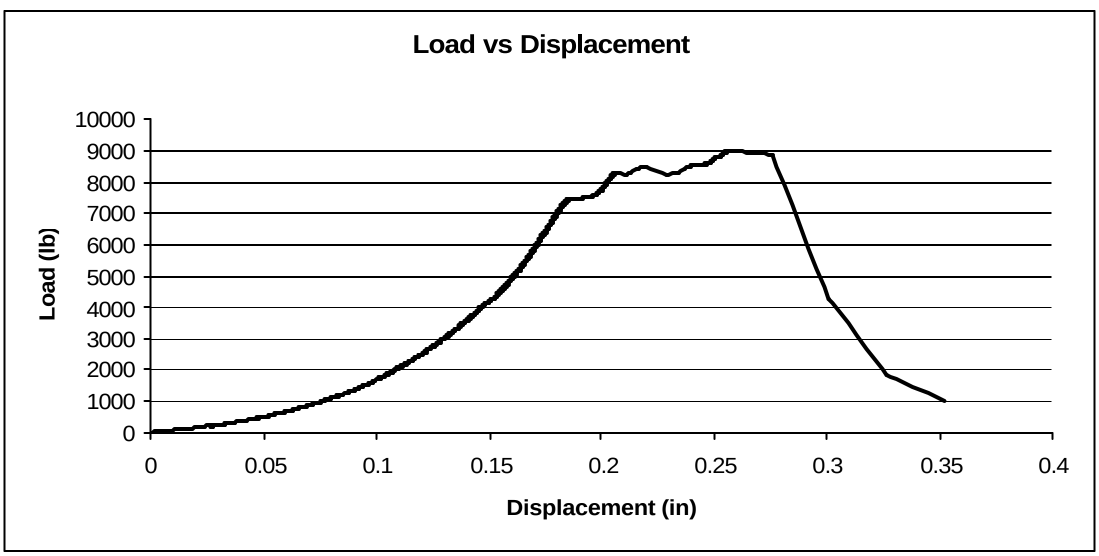

Cylinder
7422


Cylinder
7422


Load vs Displacement
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Displacement (in)

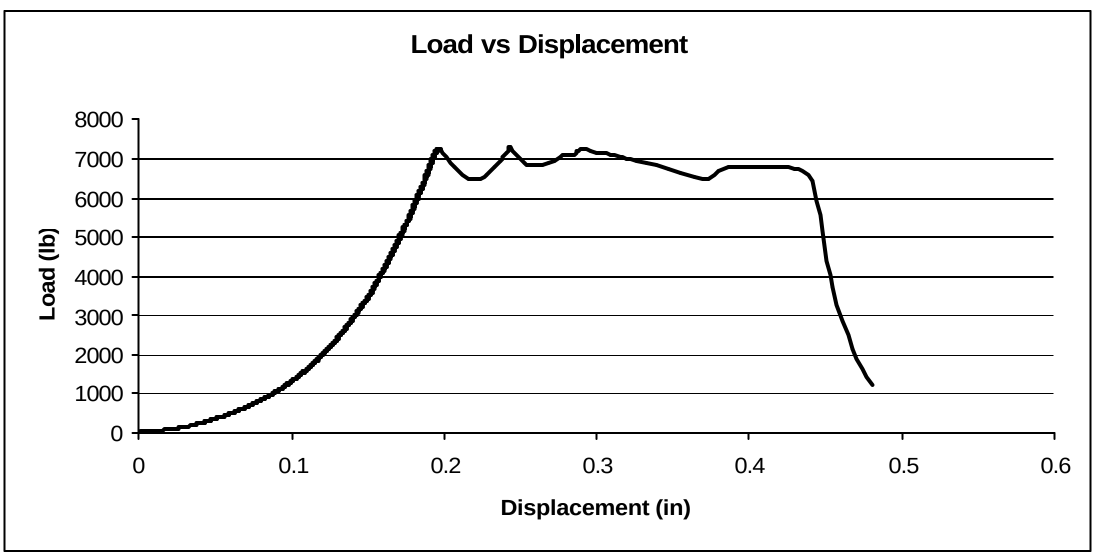

Cylinder
8411


Cylinder
8411


Load vs Displacement
Load (lb)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

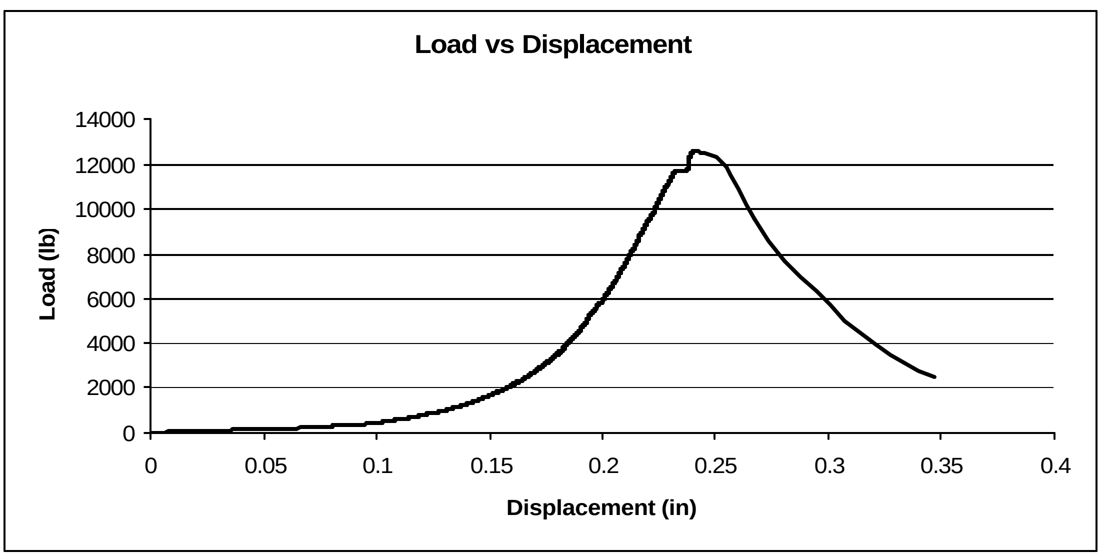

Cylinder
8412


Cylinder
8412


Load vs Displacement
Load (lb)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
Displacement (in)

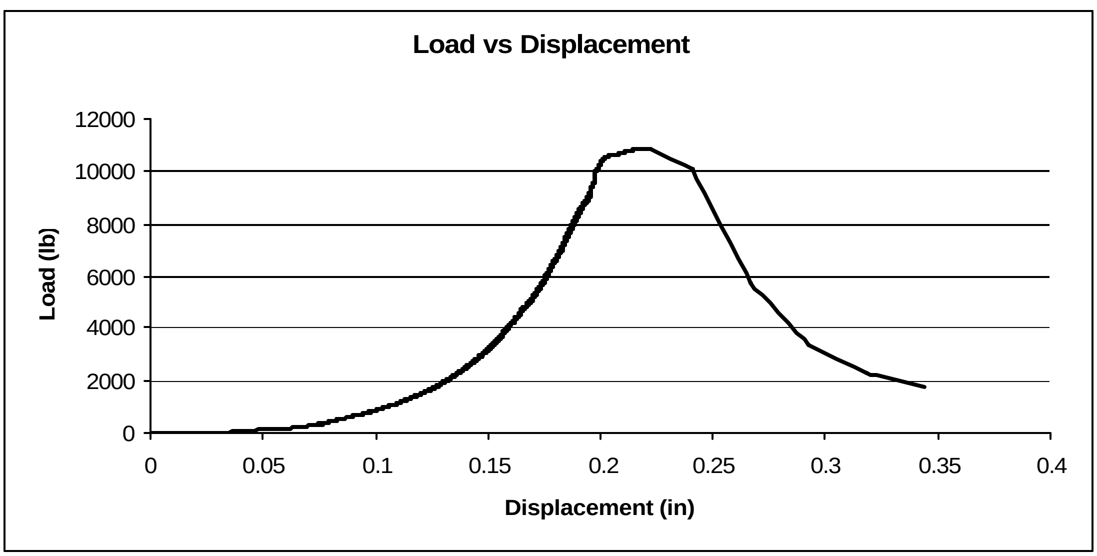

Cylinder
8421


Cylinder
8421


Load vs Displacement
Load (lb)
14000
12000
10000
8000
6000
4000
2000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)


Cylinder
8422


Cylinder
8422


Load vs Displacement
12000
10000
8000
6000
4000
2000
0
Load (lb)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in)

APPENDIX D: TABLES FOR PAVEMENT THICKNESS DESIGN

Standard Normal Deviates for Various Levels of Reliability

Reliability (%)	Standard Normal Deviate (Z)	Reliability (%)	Standard Normal Deviate (Z)
50	0.000	93	-1.476
60	-0.253	94	-1.555
70	-0.524	95	-1.645
75	-0.674	96	-1.751
80	-0.841	97	-1.881
85	-1.037	98	-2.054
90	-1.282	99	-2.327
91	-1.340	99.9	-3.090
92	-1.405	99.99	-3.750

Source: Huang (2004), Pavement Analysis and Design, p.512.

Recommended Values of Drainage Coefficient for Rigid Pavements

Quality of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	Water removed within	Less than 1%	1-5%	5-25%	Greater than 25%
Excellent	2 hours	1.25-1.20	1.20-1.15	1.15-1.10	1.10
Good	1 day	1.20-1.15	1.15-1.10	1.10-1.00	1.00
Fair	1 week	1.15-1.10	1.10-1.00	1.00-0.90	0.90
Poor	1 month	1.10-1.00	1.00-0.90	0.90-0.80	0.80
Very Poor	Never drain	1.00-0.90	0.90-0.80	0.80-0.70	0.70

Source: Huang (2004), Pavement Analysis and Design, p.581.

Load Transfer Coefficient

ESAL (millions)	Load Transfer Coefficient (J)
Up to 0.3	2.8
0.3 to 1	3.0
1 to 3	3.1
3 to 10	3.2
10 to 30	3.4
Over 30	3.6

Source: Ghafoori (1995), Journal of Transportation Engineering, p. 481.

Total Growth Factor

Design Period (years)	Annual growth rate (%)							
	No growth	2	4	5	6	7	8	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	2.0	2.02	2.04	2.05	2.06	2.07	2.08	2.10
3	3.0	3.06	3.12	3.15	3.18	3.21	3.25	3.31
4	4.0	4.12	4.25	4.31	4.37	4.44	4.51	4.64
5	5.0	5.20	5.42	5.53	5.64	5.75	5.87	6.11
6	6.0	6.31	6.63	6.80	6.98	7.15	7.34	7.72
7	7.0	7.43	7.90	8.14	8.39	8.65	8.92	9.49
8	8.0	8.58	9.21	9.55	9.90	10.26	10.64	11.44
9	9.0	9.75	10.58	11.03	11.49	11.98	12.49	13.58
10	10.0	10.95	12.01	12.58	13.18	13.82	14.49	15.94
11	11.0	12.17	13.49	14.21	14.97	15.78	16.65	18.53
12	12.0	13.41	15.03	15.92	16.87	17.89	18.98	21.38
13	13.0	14.68	16.63	17.71	18.88	20.14	21.50	24.52
14	14.0	15.97	18.29	19.60	21.02	22.55	24.21	27.97
15	15.0	17.29	20.02	21.58	23.28	25.13	27.15	31.77
16	16.0	18.64	21.82	23.66	25.67	27.89	30.32	35.95
17	17.0	20.01	23.70	25.84	28.21	30.84	33.75	40.54
18	18.0	21.41	25.65	28.13	30.91	34.00	37.45	45.60
19	19.0	22.84	27.67	30.54	33.76	37.38	41.45	51.16
20	20.0	24.30	29.78	33.07	36.79	41.00	45.76	57.27
25	25.0	32.03	41.65	47.73	54.86	63.25	73.11	98.35
30	30.0	40.57	56.08	66.44	79.06	94.46	113.28	164.49
35	35.0	49.99	73.65	90.32	111.43	138.24	172.32	271.02

Source: Huang (2004), Pavement Analysis and Design, p.271.

Truck Factors for Different Classes of Highways and Vehicles in the United States

	Rural Systems					
		Other	Minor	Collectors		
Vehicle Type	Interstate	Principal	Arterial	Major	Minor	Range
Single-Unit Trucks						
2-axle, 4-tire	0.003	0.003	0.003	0.017	0.003	0.003-0.017
2-axle, 6-tire	0.21	0.25	0.28	0.41	0.19	0.19-0.41
3-axle or more	0.61	0.86	1.06	1.26	0.45	0.45-1.26
All single units	0.06	0.08	0.08	0.12	0.03	0.03-0.12
Tractor semitrailers						
4-axle or less	0.62	0.92	0.62	0.37	0.91	0.37-0.91
5-axle	1.09	1.25	1.05	1.67	1.11	1.05-1.67
6-axle or more	1.23	1.54	1.04	2.21	1.35	1.04-2.21
All multiple units	1.04	1.21	0.97	1.52	1.08	0.97-1.52
All trucks	0.52	0.38	0.21	0.30	0.12	0.12-0.52

	Urban Systems					
		Other	Other	Minor		
Vehicle Type	Interstate	Freeways	Principal	Arterial	Collectors	Range
Single-Unit Trucks						
2-axle, 4-tire	0.002	0.015	0.002	0.006	-	0.006-0.015
2-axle, 6-tire	0.17	0.13	0.24	0.23	0.13	0.13-0.24
3-axle or more	0.61	0.74	1.02	0.76	0.72	0.61-1.02
All single units	0.05	0.06	0.09	0.04	0.16	0.04-0.16
Tractor semitrailers						
4-axle or less	0.98	0.48	0.71	0.46	0.40	0.40-0.98
5-axle	1.07	1.17	0.97	0.77	0.63	0.63-1.17
6-axle or more	1.05	1.19	0.9	0.64	-	0.64-1.19
All multiple units	1.05	0.96	0.91	0.67	0.53	0.53-1.05
All trucks	0.39	0.23	0.21	0.07	0.24	0.07-0.39

Source: Huang (2004), Pavement Analysis and Design, p.269.

REFERENCES

Aitcin, Pierre-Claude, Neville, Adam, *How the Water-Cement Ratio Affects Concrete Strength*, Concrete International, August 2003, Vol. 25, No. 8, pp 51-58.

Brown, Dan, Pervious *Concrete Pavement: A Win-Win System*, Concrete Technology Today, August 2003, Vol. 24, No. 2, pp 1-3.

Das, Braja M., *Principles of Geotechnical Engineering*, 5th ed., Brooks/Cole, California, 2002.

Ghafoori, Nader, *Development of No-Fines Concrete Pavement Applications*, Journal of Transportation Engineering, May/June 1995, Vol. 126, No. 3, pp 283-288.

Ghafoori, Nader, Laboratory *Investigation of Compacted No-Fines Concrete for Paving Materials*, Journal of Materials in Civil Engineering, August 1995, Vol. 7, No. 3, pp 183-191.

Ghafoori, Nader, *Building and Nonpavement Applications of No-Fines Concrete*, Journal of Materials in Civil Engineering, November 1995, Vol. 7, No. 4, pp 286-289.

Ghafoori, Nader, *Pavement Thickness Design for No-Fines Concrete Parking Lots*, Journal of Transportation Engineering, November/December 1995, Vol. 121, No. 6, pp 476-484.

Huang, Yang H., *Pavement Analysis and Design*, 2nd ed., Prentice Hall, New Jersey, 2004.

Klieger, Paul, *Further Studies on the Effect of Entrained Air on Strength and Durability of Concrete with Various Sizes of Aggregate*, Concrete International, November 2003, Vol. 25, No. 11, pp26-45.

Malhotra, V.M., *No-Fines Concrete – Its Properties and Applications*, ACI Journal, November 1976, Vol. 73, Issue 11, pp 628-644.

Mather, Bryant, *How much w in w/cm?*, Concrete International, August 1988, Vol. 10, No. 8, pp 20-27.

Mather, Bryant, Hime, William G., *Amount of Water Required for Complete Hydration of Portland Cement,* Concrete International, June 2002, Vol. 24, No. 6, pp 56-58.

Meininger, Richard C., *No-Fines Pervious Concrete for Paving*, Concrete International, August 1988, Vol. 10, No. 8, pp 20-27.

Trip Generation Manual, ITE, 1991.

A Policy on Geometric Design of Highways and Streets, AASHTO, 2004.

www.gcpa.org

www.epa.gov

www.chargerconcrete.com

www.georgiaplanning.com

www.rempelbros.com

www.secpa.org

www.rinker.com

www.webdesignpros.net

www.ehs.berkeley.edu

www.cityofseattle.net

www.azcentral.com

www.boattree.com

www4.nationalacademies.org

www.winnebagoind.com

www.ctea.on.ca